



62-1-1/2
233
NH

BULLETIN

OF THE

GEOLOGICAL SOCIETY

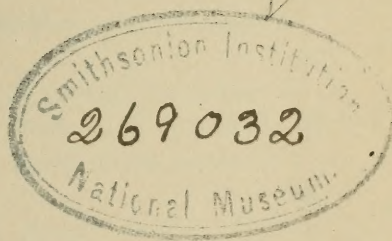
OF

AMERICA

77

VOL. 33

JOSEPH STANLEY-BROWN, *Editor*



NEW YORK
PUBLISHED BY THE SOCIETY
1922

OFFICERS FOR 1922

CHARLES SCHUCHERT, *President*

HENRY S. WASHINGTON,	} <i>Vice-Presidents</i>
ROBERT T. HILL,	
W. D. MATTHEW,	
T. L. WALKER,	

EDMUND OTIS HOVEY, *Secretary*

EDWARD B. MATHEWS, *Treasurer*

JOSEPH STANLEY-BROWN, *Editor*

Class of 1924	} <i>Councilors</i>
E. S. BASTIN,	
L. G. WESTGATE,	
Class of 1923	
L. C. GRATON,	
G. D. LOUDERBACK,	
Class of 1922	
T. W. VAUGHAN,	
GEORGE F. KAY,	

PRINTERS

JUDD & DETWEILER (INC.), WASHINGTON, D. C.

ENGRAVERS

THE MAURICE JOYCE ENGRAVING COMPANY, WASHINGTON, D. C.

CONTENTS

	Page
Proceedings of the Thirty-fourth Annual Meeting of the Geological Society of America, held at Amherst, Massachusetts, Wednesday-Friday, December 28-30, 1921; EDMUND OTIS HOVEY, <i>Secretary</i>	1
Session of Wednesday, December 28.....	6
Report of the Council.....	6
Secretary's report.....	6
Treasurer's report.....	9
Editor's report.....	11
Election of Auditing Committee.....	12
Election of Officers.....	13
Election of Correspondent.....	13
Election of Fellows.....	14
Election of representatives on the National Research Council....	15
Election of Committee on the Teaching of Geology.....	15
Necrology.....	15
Memorial of George Frederick Wright (with bibliography); by WARREN UPHAM.....	15
Memorial of Orestes Hawley Saint John (with bibliography); by CHARLES R. KEYES.....	31
Memorial of Henry Platt Cushing (with bibliography); by JAMES F. KEMP.....	44
Report of the Committee on Teaching Geology:	
Demonstration material in geology [with discussion]; by HERDMAN F. CLELAND.....	56
Titles and abstracts of papers presented before the morning session and discussions thereon.....	86
Glaciation of New Hampshire [abstract]; by JAMES WALTER GOLDTHWAIT.....	86
Recession of the land-ice in New England [abstract and discussion]; by ERNST ANTEVS.....	86
Structure of the Connecticut basin during the Newark epoch [abstract and discussion]; by WILBUR G. FOYE.....	87
Geology of Costa Rica [abstract and discussion]; by E. B. BRANSON.....	90
Titles and abstracts of papers presented before the afternoon session and discussions thereon.....	90
The Andean geosyncline [abstract and discussion]; by CHARLES SCHUCHERT.....	90
Structural relation of the Purcell Range to the Canadian Rockies [abstract and discussion]; by FRANCIS P. SHEPARD	91
Faults, underdrag, and landslides of the great basin ranges; by W. M. DAVIS.....	92
General morphologic features of Basin Range faults [abstract]; by GEORGE D. LOUDERBACK.....	96
Buried granite in Kansas [abstract and discussion]; by RAYMOND C. MOORE.....	96

	Page
Intraformational corrugated rocks [abstract and discussion]; by WILLIAM J. MILLER.....	98
Structure of the pre-Pennsylvanian rocks of the Big Stone Gap area, Wise County, Virginia [abstract]; by GEORGE W. STOSE.....	98
Relation of deep-seated faults to surface structure in the region northeast of the Yellowstone Park Plateau [ab- stract]; by W. T. THORN, JR.....	99
Possible tillite at Levis, Quebec [abstract]; by ROBERT W. SAYLES.....	99
Stages of the Ice Age [abstract]; by WARREN UPHAM.....	100
Glacial formations on the Coteau des Prairies [abstract and discussion]; by FRANK LEVERETT.....	101
What constitutes the Altamont moraine? [abstract]; by FRANK LEVERETT.....	102
Sectional meeting of Wednesday afternoon.....	104
Titles and abstracts of papers presented before the afternoon session and discussions thereon.....	104
Value of the physical characters of sand grains in the inter- pretation of the origin of sandstones [abstract and discus- sion]; by J. J. GALLOWAY.....	104
Red limestones and their geologic significance [abstract]; by J. J. GALLOWAY.....	105
Petrographic studies of some New York sediments [abstract]; by HAROLD L. ALLING.....	107
Life eras before the Cambrian [abstract]; by CHARLES R. KEYES.....	107
Quantitative study of the derivation of North American Algonkian sediments [abstract]; by ARTHUR C. TROWBRIDGE and WALDO S. GLOCK.....	108
Cambro-Ordovician section near Mount Robson, western Canada [abstract]; by LANCASTER D. BURLING.....	108
Trenton of central Tennessee and Kentucky [abstract]; by PERCY E. RAYMOND.....	109
Stratigraphy of the crystalline schists of Pennsylvania and Maryland [abstract and discussion]; by ELEANOR BLISS KNOPF and ANNA I. JONAS.....	110
Proposed new nomenclature of the Appalachian Coal Meas- ures [abstract and discussion]; by GEORGE H. ASHLEY.....	111
Revision of the Paleozoic Systems. Part II: The Ordovician System [abstract and discussion]; by E. O. ULRICH.....	112
Session of Wednesday evening.....	112
Presidential address and smoker.....	112
After effects of igneous intrusion [title]; Presidential address by JAMES F. KEMP.....	113
Session of Thursday, December 29.....	113
Report of the Auditing Committee.....	113
Symposium on isostasy.....	113

	Page
Theory of isostasy—a geological problem [title]; by WILLIAM BOWIE.....	113
Condition of the earth's crust and the earlier American gravity determinations [title]; by GEOGRE R. PUTNAM....	113
Some considerations touching on isostasy [title]; by H. O. WOOD.....	114
Isostasy and earth movements [title]; by HARRY FIELDING REID.....	114
Isostasy and applied geology [title]; by JAMES F. KEMP....	114
Folding of mountain ranges—the argument from isostasy [title]; by SIR SIDNEY BURRARD.....	114
Isostatic compensation considered as a cause of thrusting [title]; by ANDREW C. LAWSON.....	114
Isostasy and rock density [title]; by HENRY S. WASHINGTON	114
Weight of sediments per unit volume [title]; by ALFRED C. LANE.....	114
Rôle of isostatic stress [title]; by BAILEY WILLIS.....	114
Session of Thursday afternoon.....	115
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	115
Comparative study of the Nebraskan and Kansan tills in Iowa [abstract]; by GEORGE F. KAY.....	115
Further data on the differentiation of the glacial drift sheets of northern Illinois [abstract and discussion]; by M. M. LEIGHTON.....	116
Late Pleistocene history of the Lower Mohawk and Middle Hudson region [abstract]; by JAMES H. STOLLER.....	117
Ablation of the eastern lobe of the Wisconsin ice-sheet [abstract]; by JOHN H. COOK.....	117
Preliminary notes on the shorelines of glacial Lake Nashua, near Fitchburg, Massachusetts [abstract]; by THOMAS C. BROWN.....	118
Map of the Pleistocene lakes of the Basin-and-Range province, and its significance [abstract and discussion]; by O. E. MEINZER.....	118
Is the channel of the Missouri River through North Dakota of Tertiary origin? [abstract]; by JAMES E. TODD.....	120
Former courses of the Androscoggin River [abstract]; by IRVING B. CROSBY.....	121
Peneplains and the geographic cycle; by W. M. DAVIS.....	121
Retrograding of offshore bars [abstract]; by DOUGLAS W. JOHNSON.....	121
Rôle of crosswaves in the formation of tomboloes and points [abstract and discussion]; by ROSWELL H. JOHNSON.....	122
Geology of the Colorado River in southeastern Utah [abstract]; by C. R. LONGWELL, H. D. MISER, R. C. MOORE, and SIDNEY PAIGE.....	122

	Page
Cambrian succession of northwestern Vermont [abstract and discussion]; by ARTHUR KEITH.....	123
Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia [abstract]; by KENNETH C. HEALD and KIRTLEY F. MATHER.....	124
Geology of Kauai, Hawaiian Islands [abstract]; by N. E. A. HINDS.....	125
Sectional meeting of Thursday afternoon.....	126
Tubular amygdaloid from Nova Scotia [abstract]; by T. L. WALKER and A. L. PARSONS.....	126
Graphic study of igneous rock series; by FRANK F. GROUT...	127
Mount Monadnock, Vermont—a Montereian hill [abstract and discussion]; by JOHN E. WOLFF.....	127
Geology of the Pawtuckaway Mountains [abstract]; by E. S. C. SMITH.....	128
Evidences of assimilation during the Katmai eruption of 1912 [abstract]; by C. N. FENNER.....	129
Tridymite-orthoclase rock, a new metamorphic rock type from Imperial County, California [abstract and discussion]; by AUSTIN F. ROGERS.....	129
Genetic features of alnoitic rocks from Isle Cadieux, Quebec [abstract]; by N. L. BOWEN.....	130
Sillimanite-schist inclusions in granite [abstract]; by W. J. MILLER.....	130
Preliminary notes on some regularly banded argillites which suggest seasonal deposition [abstract]; by ROBERT W. SAYLES	133
Session of Thursday evening.....	134
Annual dinner.....	134
Presentation of loving cup to Prof. B. K. Emerson.....	134
Greetings from Section E, American Association for the Advancement of Science.....	135
Session of Friday, December 30.....	136
Vote of thanks.....	136
Report of the Council Committee on Policy.....	136
Titles and abstracts of papers presented at the morning session and discussions thereon.....	138
Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina [abstract and discussion]; by KIRTLEY F. MATHER.....	138
Some astronomical tests of the planetesimal hypothesis [abstract]; by HARRY FIELDING REID.....	140
Marginal belts of the coral seas [abstract]; by W. M. DAVIS	140
Transgressions, regressions, and shoreline displacements during the Pleistocene [title]; by CHESTER A. REEDS.....	140
Old and new standards of Pleistocene subdivision [title]; by HENRY FAIRFIELD OSBORN and CHESTER A. REEDS.....	140
Is the present the first of a new chapter? [abstract]; by A. C. LANE.....	141

	Page
Hot springs of Lassen National Park [abstract]; by A. L. DAY and E. T. ALLEN.....	141
Recent eruption of Lassen Peak [abstract]; by A. L. DAY and E. T. ALLEN.....	141
Surface fusion of lava; by J. S. DILLER.....	142
A source of heat in volcanic activity [abstract and discussion]; by LEASON H. ADAMS.....	144
Use of foraminifera in determining underground structure, especially in petroleum mining [abstract]; by J. A. CUSHMAN.....	145
Session of Friday afternoon.....	146
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	146
Deccan traps and other plateau basalts [abstract]; by HENRY S. WASHINGTON.....	146
Geology of the Guilford, Connecticut, quadrangle [abstract and discussion]; by WILBUR G. FOYE.....	147
Jasperoid of the Joplin district, Missouri, Kansas, and Oklahoma [abstract]; by W. S. TANGIER SMITH.....	147
Transitional coals and their bearing on hypothesis of the origin of coals [abstract]; by EDWARD C. JEFFREY.....	148
Organization of Pennsylvania anthracite and the peat hypothesis of the origin of coal [abstract and discussion]; by EDWARD C. JEFFREY.....	149
Ore deposits of Leadville, Colorado [abstract]; by G. F. LOUGHLIN.....	149
Antimony mines of Shiu Chow, China [abstract]; by GEORGE D. HUBBARD.....	149
Source of the sulphates in the Salina beds [abstract]; by DAVID H. NEWLAND.....	150
Flooding of oil wells by fresh water [abstract]; by THOMAS C. BROWN.....	151
Sectional session of Friday afternoon.....	151
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	151
Oriskany of Oklahoma [abstract and discussion]; by CHARLES SCHUCHERT.....	151
Age of the Talladega phyllite [abstract]; by WILLIAM F. PROUTY.....	151
Constitution of the Ohio black shales [abstract and discussion]; by GEORGE H. CHADWICK.....	152
Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama [abstract and discussion]; by WILBUR A. NELSON.....	152
Strata near Stuart, Iowa [abstract]; by JOHN L. TILTON....	153
Environment of the early Permian insects of Kansas [abstract and discussion]; by CARL O. DUNBAR.....	153

	Page
Some cavern deposits in the Permian in west Texas; by J. A. UDDEN.....	153
Paleozoic-Mesozoic contact throughout Wyoming [abstract]; by S. H. KNIGHT.....	155
Stratigraphy of the Lower Oreodon beds of the South Dakota Big Badlands [abstract and discussion]; by WILLIAM J. SINCLAIR.....	155
Discussion of the Pleistocene and its vertebrate faunas [abstract and discussion]; by OLIVER P. HAY.....	156
Licks and caves of the Lower Ohio Valley as repositories of mammalian remains, including those of man; by ARTHUR M. MILLER.....	156
Correlation of the Jurassic formations of western Cuba [abstract and discussion]; by BARNUM BROWN and MARJORIE O'CONNELL.....	159
Register of the Amherst meeting, 1921.....	160
Constitution and By-Laws.....	162
Officers, Correspondents, and Fellows of the Geological Survey of America.....	173
Proceedings of the Twentieth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 26, 1921; AUSTIN F. ROGERS, <i>Secretary</i>	187
Session of March 26.....	188
Election of officers for 1921.....	188
Program of papers.....	188
Correlation and paleogeography of the marine Tertiary of California [title]; by BRUCE L. CLARK.....	188
Probable occurrence of massive troilite in serpentine [title]; by A. S. EAKLE.....	188
Jurupaite, a new mineral from Crestmore, California [title]; by A. S. EAKLE.....	188
Late Tertiary mammalian remains from near Alturas, north-eastern California [title]; by CHESTER STOCK.....	188
Marsupial from the John Day Oligocene of Logan Butte, Oregon [title]; by CHESTER STOCK and E. L. FURLONG.....	189
Mechanics of the San Andreas fault [title]; by BAILEY WILLIS	189
Certain marked differential movements in the San Francisco Bay region [title]; by G. D. LOUDERBACK.....	189
Jasperoid of the Joplin District, Missouri, Kansas, and Oklahoma [title]; by W. S. TANGIER SMITH.....	189
Collophane, a much-neglected mineral [title]; by AUSTIN F. ROGERS	189
Discussion of the age of Briones formation of middle California [title]; by P. D. TRASK.....	189
Montezuma Hills [title]; by G. A. WILCOX.....	189
Some new aspects of the geology at Cobalt [title]; by A. R. WHITEMAN	189
Business session of the Section.....	190

	Page
Register of the California meeting, 1921.....	190
Proceedings of the Thirteenth Annual Meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921; R. S. BASSLER, <i>Secretary</i>	191
Session of Wednesday, December 28.....	193
Session of Thursday, December 29.....	193
Report of the Council.....	193
Secretary's report.....	193
Treasurer's report.....	194
Appointment of Auditing Committee.....	195
Election of officers and members.....	195
New nominations and election to membership.....	196
Presentation of papers.....	196
Nature of <i>Salterella</i> [abstract]; by THOMAS H. CLARK.....	196
Possible habits of cephalopods and trilobites [abstract]; by PERCY E. RAYMOND.....	197
Historical sketch of paleopathology [abstract]; by ROY L. MOODIE	197
<i>Oldhamia</i> in the Lower Cambrian of Massachusetts [abstract]; by B. F. HOWELL.....	198
Nature of <i>Taonurus</i> and its use in estimating geologic time [abstract]; by J. J. GALLOWAY.....	199
Pennsylvania faunas of north Texas and their correlation [abstract]; by RAYMOND C. MOORE.....	199
Unattached simple Paleozoic corals [abstract]; by AUGUST F. FOERSTE	201
Devonian limestone at Saint George, Quebec [abstract]; by THOMAS H. CLARK.....	201
Age of the coal beds of the Kaiping coal basin, in northeastern China [abstract]; by A. W. GRABAU.....	201
Ordovician formation of north China [abstract]; by A. W. GRABAU	202
Presidential address.....	203
Some problems connected with the Dakota sandstone: Presidential address by T. W. STANTON.....	203
Supplement to the bibliography and catalogue of the fossil vertebrates of North America; by O. P. HAY.....	203
Flora of the Payette formation [abstract]; by RALPH W. CHANEY	203
Flora of the Rancho La Brea [abstract]; by RALPH W. CHANEY	204
Pines of the Mesozoic and their relationship to older and more modern types [abstract]; by EDWARD C. JEFFREY....	204
Ordovician "Hypoparian" genera of trilobites [abstract]; by E. O. ULRICH.....	205
Limits of variations in foraminifera; by J. A. CUSHMAN....	206
Recent geological work in Gulf Coast oil fields; by E. T. DUMBLE	207

	Page
Mohawkian and Cincinnatian rocks of central Tennessee [abstract]; by R. S. BASSLER.....	207
Session of Friday, December 30.....	207
Report of the Auditing Committee.....	207
Presentation of papers.....	207
Few more facts bearing on the correlation of the Chester formations; by E. O. ULRICH.....	208
Occurrence of the Parichnos of Bertrand in certain gymnosperms [abstract]; by E. C. JEFFREY.....	208
Age and development of red beds and the terrestrial vertebrates in the Appalachian and the Kansas-Texas region [abstract]; by J. W. BEEDE.....	208
Methods of studying Ammonites; by MARJORIE O'CONNELL..	209
Lunar petrefactions; by F. W. SARDESON.....	209
Section of Vertebrate Paleontology.....	209
Presentation of papers.....	209
Fossils of the Connecticut Valley [abstract]; by E. I. TROXELL	209
Hyracodons from the Big Badlands of South Dakota; by W. J. SINCLAIR	209
Relationship of the Great Basin and Great Plains fauna [abstract]; by E. L. TROXELL.....	210
Restoration of <i>Blastomeryx</i> ; by R. S. LULL.....	211
Supposed Labyrinthodont footprints from the Maryland Carboniferous [abstract]; by R. S. LULL.....	211
Upper Pawnee Creek beds [abstract]; by F. B. LOOMIS.....	211
Lower Miocene at Van Tassel, Wyoming; by F. B. LOOMIS...	211
Huge amphibian from the Upper Coal Measures of Kansas [abstract]; by H. T. MARTIN.....	212
Primitive and carnivore-like characters of the Merycoidodontidae [abstract]; by M. R. THORPE.....	212
Restoration of <i>Eporeodon socialis</i> , Marsh [abstract]; by M. R. THORPE	213
New light on the phylogeny of the Canidae; by W. D. MATTHEW	214
Tooth of almost human type from the Lower Pliocene Snake Creek beds of Western Nebraska; by HAROLD J. COOK.....	214
<i>Aræocyon</i> , a probable Old World migrant [abstract]; by M. R. THORPE	214
Snake Creek fauna; by W. D. MATTHEW.....	215
Phylogeny and nomenclature of the Proboscidea; by H. F. OSBORN	215
Register of the Amherst meeting, 1921.....	216
Officers, Correspondents, and Members of the Paleontological Society.	217
Proceedings of the First Annual Meeting of the Society of Economic Geologists, Amherst, Massachusetts, December 28-30, 1921; SYDNEY H. BALL, Secretary	223
Session of Wednesday, December 28.....	223

	Page
Election of officers for 1922.....	223
Presentation of papers.....	224
Session of Thursday, December 29.....	225
Presentation of papers.....	225
Session of Friday, December 30.....	225
Presentation of papers.....	225
Proceedings of the Second Annual Meeting of the Mineralogical Society of America, held at Amherst, Massachusetts, December 29, 1921; HER- BERT P. WHITLOCK, <i>Secretary</i>	227
Session of Thursday, December 29, 1921.....	227
Election of officers for 1922.....	227
Report of the Secretary.....	228
Report of the Treasurer.....	228
Report of the Editor.....	228
Report of the Committee on Nomenclature and Classification of Minerals	228
Presentation of papers.....	229
After-effects of igneous intrusion; Presidential address by JAMES F. KEMP	231
Some problems connected with the Dakota sandstone; Presidential ad- dress by TIMOTHY W. STANTON.....	255
Theory of isostasy—a geological problem; by W. BOWIE.....	273
Condition of the earth's crust and the earlier American gravity observa- tions; by G. R. PUTNAM.....	287
Some considerations touching on isostasy; by H. O. WOOD.....	303
Isostasy and earth movements; by H. F. REID.....	317
Isostasy and applied geology; by J. F. KEMP.....	327
Folding of mountain ranges—the argument from isostasy; by SIR SIDNEY BURRARD	333
Isostatic compensation considered as a cause of thrusting; by A. C. LAWSON	337
Weight of sedimentary rocks per unit of volume; by A. C. LANE.....	353
Rôle of isostatic stress; by B. WILLIS.....	371
Isostasy and rock density; by H. S. WASHINGTON.....	375
Old and new standards of Pleistocene division in relation to the prehis- tory of man in Europe; by H. F. OSBORN and C. A. REEDS.....	411
Stages of the Ice Age; by W. UPHAM.....	491
Late Pleistocene history of the lower Mohawk and middle Hudson region; by J. H. STOLLER.....	515
Kennecott glacier of Alaska; by A. M. BATEMAN.....	527
Map of the Pleistocene lakes of the Basin-and-Range province and its sig- nificance; by O. E. MEINZER.....	541
Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia; by K. C. HEALD and K. F. MATHER.....	553
Trenton of central Tennessee and Kentucky; by P. E. RAYMOND.....	571
Peneplains and the geographical cycle; by W. M. DAVIS.....	587
Variations or specific distinctions: which? by R. S. LULL.....	599
Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama; by W. A. NELSON.....	605
Graphic study of igneous rock series; by F. F. GROUT.....	617

	Page
Correlation of the Jurassic formations of western Cuba; by B. BROWN and MARJORIE O'CONNELL.....	639
Devonian of Oklahoma, with special reference to the Oriskany and Camden formations; by CHARLES SCHUCHERT.....	665
Age and development of red beds and terrestrial vertebrates of the Appalachian and Kansas-Texas sections; by J. W. BEEDE.....	671
Strata near Stuart, Iowa; by J. L. TILTON.....	689
Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina; by K. F. MATHER.....	703
Deccan traps and other plateau basalts; by H. S. WASHINGTON.....	765
Some new facts bearing on correlations of Chester formations; by E. O. ULRICH.....	805
Index to volume 33.....	853

ILLUSTRATIONS

PLATES

Plate 1—UPHAM: Portrait of G. Frederick Wright.....	15
“ 2—KEYES: Portrait of O. H. Saint John.....	31
“ 3—KEMP: Portrait of H. P. Cushing.....	44
“ 4—STANTON: Columnar sections of Dakota and associated formations.....	257
“ 5 “ Map showing location of sections and distribution of Washita and “Middle Dakota” faunas.....	258

FIGURES

CLELAND:

Figures 1, 2, and 3—Model to show the effect of two faults at right angles to each other.....	61
Figure 4—Model which shows slip, dip-slip, net-shift, and drag-dip	62
Figures 5, 6, and 7—Model to show the topographic effect of a dip-fault, before and after erosion.....	63
Figure 8—Sedimentary erosion apparatus in use at the University of Wisconsin.....	66
“ 9—Model of a part of Valcour Island, Lake Champlain, New York.....	68
“ 10—Model of a gold mine, Field Museum of Natural History	69
“ 11—Model of a coal mine, Field Museum of Natural History	70
“ 12—Model of the Mount Greylock (Massachusetts) synclinalorium.....	71
“ 13—Model of a Mexican oil field.....	72
“ 14—Another view of the model shown in figure 13, top removed.....	73
“ 15—Example of a relatively inexpensive exhibition useful in teaching.....	74

DAVIS:

Figure 1—An overthrust, O, leaving a cavity, G, behind it.....	93
“ 2—An overthrust, O, emerging from beneath the crust, AB, which is displaced and extended by “underdrag”....	93

LEVERETT:

- Figure 1—Map of the Des Moines icelobe..... 103

MILLER:

- Figure 1—Sillimanite-schist inclusions in granite near south Russell, New York..... 131

DILLER:

- Figure 1—Basaltic lava from San Salvador, Central America.... 143
 “ 2—New lava from Lassen Peak, California..... 144

PUTNAM:

- Figure 1—Diagram illustrating three methods, used in 1895, of reduction of gravity observations to sealevel, for two stations, located one above and the other below the average elevation..... 292

WOOD:

- Figure 1—Diagram to illustrate growth of stresses with depth... 308

LAWSON:

- Figure 1—Diagrammatic representation of a thrust block..... 337
 “ 2—Diagram to show the increase in the coefficient of friction with increasing pressure (after Rennie)..... 339
 “ 3—Diagrammatic representation of a thrust block..... 342
 “ 4—Diagrammatic representation of a thrust block..... 343
 “ 5—Diagrammatic representation of a thrust block, showing failure due to underthrusting..... 345
 “ 6—Diagram illustrating thrusting by rotation..... 347
 “ 7—Diagram illustrating thrusting by a current moving from right to left below the crust..... 348
 “ 8—Diagram illustrating the initiation of a curved thrust, D, in depth and its propagation toward the surface.. 348
 “ 9—Diagram illustrating the development of the curved thrust, PQ, as a result of isostatic compensation..... 349

LANE:

- Figure 1—Diagram showing by ordinates the weight in tons per cubic meter and per cent of moisture absorbable of sediments of porosity indicated by abscissas..... 359

WASHINGTON:

- Figure 1—Continental and oceanic densities and altitudes..... 394
 “ 2—Densities and altitudes of land areas..... 396

OSBORN AND REEDS:

- Figure 1—Map of central and southern European glaciations..... 416
 “ 2—Graphic presentation of the relation of the Pleistocene glacial phenomena of the Alps to the river and marine terraces of Europe..... 428
 “ 3—Map of north European glaciation..... 442
 “ 4—Cross-section of the terraces on the river Somme at Saint Acheul, northern France..... 448
 “ 5—Quarry section of Chelles-sur-Marne..... 450
 “ 6—Cross-section of the valley of the river Elsenz at Mauer, Germany, near Heidelberg..... 453

OSBORN AND REEDS:

Figure 7—Sand-pit at Mauer, near Heidelberg, the discovery site of the jaw of the Heidelberg man, <i>Homo heidelbergensis</i>	454
" 8—Excavations on the "high terrace" [II] at Saint Acheul	456
" 9—Liege Paleolithic, Belgium.....	458
" 10—Section of the Hesbayen loess, Saint Walburge, Belgium	460
" 11—Graphic presentation of the last Alpine [Würm] glaciation.....	466
" 12—Normal climatic curve of glacial and interglacial times	468
" 13—Correlation of marine, terrace, climatic, racial, culture, and life stages of the Pleistocene and Upper Pliocene periods.....	470
" 14—Retreat phases of the fourth glaciation in north central Germany (after Soergel).....	477

STOLLER:

Figure 1—Sketch map of the lower Mohawk-middle Hudson region	520
--	-----

BATEMAN:

Figure 1—Index map of part of Alaska.....	528
" 2—Kennecott glacier, showing moraines, Mount Blackburn in distance.....	529
" 3—Map of Kennecott glacier, its tributaries and gathering grounds.....	531
" 4—View of edge of glacier opposite Kennecott.....	533
" 5—Narrow A-shaped moraine parallel to edge of glacier and higher than top of glacier.....	534
" 6—Map showing position of stakes and movement of Kennecott glacier.....	537
" 7—Curve showing relation between the amount of movement of glacier and distance from edge of glacier....	539

MEINZER:

Figure 1—Map of the Pleistocene lakes in the Basin-and-Range province.....	543
" 2—Map of the present lakes in the Basin-and-Range province.....	545
" 3—Map of part of the North Basin of Big Smoky Valley, Nevada.....	547
" 4—Map comparing the Pleistocene lake and the present areas of ground-water discharge in the North Basin of Big Smoky Valley, Nevada.....	548

HEALD AND MATHER:

Figure 1—The Cordillera Oriental between Cochabamba and Santa Cruz, Bolivia.....	554
" 2—Cochabamba-Santa Cruz geology.....	556
" 3—Cochabamba-Santa Cruz geology.....	557
" 4—Cochabamba-Santa Cruz geology.....	562
" 5—Cochabamba-Santa Cruz geology.....	564
" 6—Cochabamba-Santa Cruz geology.....	566
" 7—Cochabamba-Santa Cruz geology.....	568

GROUT :

- Figure 1—Distribution of standard rock families in a diagram showing alkalies and silica..... 622
- “ 2—Eight series of rocks plotted for each analyzed specimen 624
- “ 3—Rock series showing gradations in single masses..... 626
- “ 4—Series supposed to be related genetically, but not showing clear gradations in the whole range of specimens. 627

BROWN AND O'CONNELL :

- Figure 1—Block diagram of a section of the eastern part of Pinar del Rio Province and northern end of Isle of Pines... 642
- “ 2—Lusitanian and Kimmeridgian black shales..... 644
- “ 3—Section of west side of river San Diego de los Baños... 646
- “ 4—Oxfordian and Lusitanian black shales with ammonite accretions 647
- “ 5—Organ Mountains..... 647
- “ 6—Puerta Ancón, looking north..... 648
- “ 7—Details of cliff shown in figure 6..... 649
- “ 8—View looking north toward Esperanza from center of mountain valley near San Vicente..... 649
- “ 9—A limestone magote..... 650
- “ 10—A limestone magote..... 650
- “ 11—Accretions filled with ammonites, fishes, and marine reptiles 651
- “ 12—Folded schists north of the limestone mountains on the road to Esperanza..... 652
- “ 13—Ideal cross-section showing the marine progressive overlap of the successive Middle and Upper Jurassic formations from Viñales to Candelaria..... 654
- “ 14—Ideal cross-section showing the early Tertiary folding and elevation of the strata represented in figure 13.. 654
- “ 15—Paleogeographic map showing the maximum transgression of the sea during Portlandian time..... 662

TILTON :

- Figure 1—Location of the area near Stuart, Iowa..... 690
- “ 2—Map of the area near Stuart, Iowa..... 692
- “ 3—Section from Bridgewater to Glendon, A—B on the map of the area..... 694
- “ 4—Section from Glendon to Winterset, B—C on the map of the area..... 694

MATHER :

- Figure 1—Map of the Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina..... 705
- “ 2—The Sierra de Florida..... 708
- “ 3—East side of the Sierra de Charagua..... 710
- “ 4—Sierra de Charagua, looking northward..... 712
- “ 5—Gorge of Rio Saipuru..... 714
- “ 6—North end of the Sierra de Aguarague..... 716
- “ 7—Canyon of Rio Vitiacua, in the Sierra de Aguarague... 718

MATHIER:

Figure 8—El Chorro, in the canyon through which Rio Vitiacua traverses the Sierra de Aguarague near Machareti...	720
" 9—Gorge in the eastern half of the Sierra de Aguarague..	722
" 10—Dip slope of the westernmost hogback of the Cuestas de Pipi.....	724
" 11—Sierra de Aguarague.....	728
" 12—Lowest beds in the Sierra de Mandiyuti.....	732
" 13—Machareti formation.....	738
" 14—West portal to gorge cut by the Rio Charagua through the Sierra de Charagua.....	740
" 15—Upper sandstone member of the Tacuru formation....	742
" 16—Conglomerate in the basal part of the Tacuru formation	744
" 17—Steeply inclined, fossiliferous beds of the Tatarenda formation	748
" 18—Diagrammatic sections across Front ranges of the Andes in central Bolivia.....	751
" 19—Tectonic map of the area shown in figure 1.....	752
" 20—Sketch map and structure section of a portion of the Sierra de Charagua, Bolivia.....	754
" 21—North bank of Rio Parapiti.....	756

WASHINGTON:

Figure 1—Sketch map of the distribution of the Deccan traps....	767
" 2—Sketch map showing the main central area of the Siberian basalts.....	791

ULRICH:

Figure 1—Sketch map showing localities studied.....	823
" 2—Correlated lower Chester or Montesana sections.....	826

(5 plates; 115 figures.)

PUBLICATIONS OF THE GEOLOGICAL SOCIETY OF AMERICA

REGULAR PUBLICATIONS

The Society issues annually, in four quarterly parts, a single serial octavo publication entitled BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA, the edition being 750 copies. A small supply of authors' separates of the longer articles is kept for sale by the Secretary at the prices quoted in each volume.

The BULLETIN is sold at the uniform price of ten dollars (\$10.00) per volume, with a discount of twenty-five (25) per cent to Fellows of the Society. A discount of ten (10) per cent is allowed to persons residing elsewhere than in North America and public and institutional libraries; carriage extra. Subscriptions are payable in advance. Regular subscribers within the United States of America and its possessions receive their parts, postage paid, as issued. Forty (40) cents per volume must be added to the subscription price to cover postage to other countries in the Postal Union.

The price of the index to volumes 1-10 is \$2.25; to volumes 11-20, \$3.50, and to volumes 21-30, \$4.00; carriage extra. No reduction is made to dealers. Orders should be addressed to the Secretary, whose address is care of the American Museum of Natural History, New York, N. Y., and drafts and money orders should be made payable to *The Geological Society of America*.

DESCRIPTION OF THE PUBLISHED VOLUMES

VOLUMES.	PAGES.	PLATES.	FIGURES.
Vol. 1, 1889.....	593 + xii	13	51
Vol. 2, 1890.....	622 + xiv	23	63
Vol. 3, 1891.....	541 + xi	17	72
Vol. 4, 1892.....	458 + xi	10	55
Vol. 5, 1893.....	655 + xii	21	43
Vol. 6, 1894.....	528 + x	27	40
Vol. 7, 1895.....	558 + x	24	61
Vol. 8, 1896.....	446 + x	51	29
Vol. 9, 1897.....	460 + x	29	49
Vol. 10, 1898.....	534 + xii	54	83
Index to volumes 1-10.....	209	..	..
Vol. 11, 1899.....	651 + xii	58	37
Vol. 12, 1900.....	538 + xii	45	28
Vol. 13, 1901.....	583 + xii	58	47
Vol. 14, 1902.....	609 + xii	65	43
Vol. 15, 1903.....	636 + x	59	16
Vol. 16, 1904.....	636 + xii	94	74
Vol. 17, 1905.....	785 + xiv	84	96
Vol. 18, 1906.....	717 + xii	74	59
Vol. 19, 1907.....	617 + x	41	31
Vol. 20, 1908.....	749 + xiv	111	35
Index to volumes 11-20.....	422	..	..
Vol. 21, 1909.....	823 + xvi	54	109
Vol. 22, 1910.....	747 + xii	31	66
Vol. 23, 1911.....	758 + xvi	43	44
Vol. 24, 1912.....	737 + xviii	36	60
Vol. 25, 1913.....	802 + xviii	28	47
Vol. 26, 1914.....	504 + xxi	27	41
Vol. 27, 1915.....	739 + xviii	30	55
Vol. 28, 1916.....	1005 + xxii	48	102
Vol. 29, 1917.....	679 + xix	22	67
Vol. 30, 1918.....	644 + xiii	15	40
Index to volumes 21-30.....	325	..	..
Vol. 31, 1919.....	450 + xviii	14	7
Vol. 32, 1920.....	488 + xviii	12	60
Vol. 33, 1921.....	862 + xxi	5	115

PARTS OF VOLUME 33

	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Number 1.....	1-272	5	21	\$2.85	\$4.25
Number 2.....	273-410	...	13	1.35	2.05
Number 3.....	411-664	...	52	2.55	3.80
Number 4*.....	665-862	...	29	1.95	2.90

REPRINTS FROM VOLUME 33

REPRINTS.	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Proceedings of the Thirty-fourth Annual Meeting of the Geological Society of America, held at Amherst, Massachusetts, Wednesday-Friday, December 28-30, 1921. E. O. HOVEY, <i>Secretary</i> ..	1-186	1-3	1-21	\$1.95	\$2.90
Proceedings of the Twentieth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 26, 1921. A. F. ROGERS, <i>Secretary</i> .	187-190	....	....	.10	.15
Proceedings of the Thirteenth Annual Meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921. R. S. BASSLER, <i>Secretary</i> †	191-222	....	....	.30	.45
Proceedings of the Third Annual Meeting of the Society of Economic Geologists, held at Amherst, Massachusetts, December 28-30, 1921. S. H. BALL, <i>Secretary</i>	223-226	....	....	.10	.15
Proceedings of the Second Annual Meeting of the Mineralogical Society of America, held at Amherst, Massachusetts, December 29, 1921. H. P. WHITLOCK, <i>Secretary</i>	227-230	....	....	.10	.15
After-effects of igneous intrusion. J. F. KEMP.....	231-254	....	....	.25	.35
Some problems connected with the Dakota sandstone. T. W. STANTON	255-272	4-5	....	.25	.35
Theory of isostasy—a geological problem. W. BOWIE.....	273-286	....	....	.15	.25
Condition of the earth's crust and the earlier American gravity observations. G. R. PUTNAM	287-302	....	1	.15	.25
Some considerations touching on isostasy. H. O. WOOD.....	303-316	....	1	.15	.25
Isostasy and earth movements. H. F. REID.....	317-326	....	....	.10	.15
Isostasy and applied geology. J. F. KEMP.....	327-332	....	....	.10	.15

* Preliminary pages and index are distributed with number 4.

† Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

REPRINTS.	PAGES.	PLATES. FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Folding of mountain ranges—the argument from isostasy. SIR SIDNEY BURRARD.....	333-336	....	\$0.10	\$0.15
Isostatic compensation considered as a cause of thrusting. A. C. LAWSON.....	337-352	 1-9	.15	.25
Weight of sedimentary rocks per unit volume. A. C. LANE.....	353-370	 1	.20	.30
Rôle of isostatic stress. B. WILLIS	371-374	....	.10	.15
Isostasy and rock density. H. S. WASHINGTON	375-410	 1-2	.35	.50
Old and new standards of Pleistocene division in relation to the prehistory of man in Europe. H. F. OSBORN and C. A. REEDS	411-490	 1-14	.80	1.20
Stages of the Ice Age. W. UPHAM	491-514	....	.25	.35
Late Pleistocene history of the lower Mohawk and middle Hudson region. J. H. STOLLER.	515-526	 1	.10	.15
Kennecott glacier of Alaska. A. M. BATEMAN.....	527-540	 1-7	.15	.25
Map of the Pleistocene lakes of the Basin-and-range province and its significance. O. E. MEINZER	541-552	 1-4	.10	.15
Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia. K. C. HEALD and K. F. MATHER.....	553-570	 1-7	.20	.30
Trenton of central Tennessee and Kentucky. P. E. RAYMOND....	571-586	....	.15	.35
Peneplains and the geographical cycle. W. M. DAVIS.....	587-598	....	.10	.15
Variations or specific distinctions: which? R. S. LULL....	599-604	....	.10	.15
Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama. W. A. NELSON..	605-616	....	.10	.15
Graphic study of igneous rock series. F. F. GROUT.....	617-638	 1-4	.20	.30
Correlation of the Jurassic formations of western Cuba. B. BROWN and MARJORIE O'CONNELL	639-664	 1-15	.25	.35
Devonian of Oklahoma, with special reference to the Oriskany and Camden formations. C. SCHUCHERT	665-670	....	.10	.15
Age and development of red beds and terrestrial vertebrates of the Appalachian and Kansas-Texas sections. J. W. BEEDE†.	671-688	....	.20	.30
Strata near Stuart, Iowa. J. L. TILTON	689-702	 1-4	.15	.25
Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina. K. F. MATHER	703-764	 1-21	.60	.90

† Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

REPRINTS.	PAGES.	PLATES.	FIGURES.	PRICE TO FELLOWS.	PRICE TO PUBLIC.
Deccan traps and other plateau basalts. H. S. WASHINGTON...	765-804	....	1-2	\$0.40	\$0.60
Some new facts bearing on correlations of Chester formations. E. O. ULRICH†.....	805-852	....	1-2	.50	.75

IRREGULAR PUBLICATIONS

In the interest of exact bibliography, the Society takes cognizance of all publications issued wholly or in part under its auspices. Each author of a memoir receives 40 copies without cost, and is permitted to order any additional number at a slight advance on cost of paper and presswork; and these reprints are identical with those of the editions issued and distributed by the Society; but the cover bears only the title of the paper, the author's name, and the statement [Reprinted from the Bulletin of the Geological Society of America, vol. —, pp. —, pl. — (Date)]. Contributors to the Proceedings and "Abstracts of Papers" are also authorized to order any number of separate copies of their papers at a slight advance on cost of paper and presswork; but such separates are bibliographically distinct from the reprints issued by the Society.

Regular Editions

Pages 231-254,	250 copies.	March	31, 1922.
" 255-272, plates 4-5,	300 "	"	31, 1922.
" 273-286,	250 "	June	30, 1922.
" 287-302,	150 "	"	30, 1922.
" 303-316,	250 "	"	30, 1922.
" 317-326,	100 "	"	30, 1922.
" 327-332,	450 "	"	30, 1922.
" 333-336,	150 "	"	30, 1922.
" 337-352,	200 "	"	30, 1922.
" 353-370,	850 "	"	30, 1922.
" 371-374,	150 "	"	30, 1922.
" 375-410,	750 "	"	30, 1922.
" 411-490,	700 "	July	3, 1922.
" 491-514,	50 "	September	1, 1922.
" 515-526,	50 "	"	1, 1922.
" 527-540,	150 "	"	1, 1922.
" 541-552,	150 "	"	1, 1922.
" 553-570,	140 "	"	30, 1922.
" 571-586,	120 "	"	30, 1922.
" 587-598,	100 "	"	30, 1922.
" 599-604,	150 "	"	30, 1922.
" 605-616,	300 "	"	30, 1922.
" 617-638,	120 "	"	30, 1922.
" 639-664,	200 "	"	30, 1922.
" 665-670,	250 "	November	2, 1922.
" 671-688,*†	350 "	"	2, 1922.
" 689-702,	150 "	"	2, 1922.
" 703-764,	150 "	"	2, 1922.
" 765-804,	750 "	"	2, 1922.
" 805-852,*†	400 "	"	2, 1922.

* Bearing on the cover

PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

[Reprinted from the Bulletin of the Geological Society of America, vol. —, pp. —, pls. —, (Date).]

† Under the brochure heading is printed PROCEEDINGS OF THE PALEONTOLOGICAL SOCIETY.

Special Editions ‡

Pages	15- 30,	plate 1,	50 copies.	March	31, 1922.
"	31- 44,	" 2,	150 "	"	31, 1922.
"	44- 55,	" 3,	150 "	"	31, 1922.
"	56- 85,		250 "	"	31, 1922.
"	92- 96,		50 "	"	31, 1922.
"	147-148,		75 "	"	31, 1922.
"	153-155,		50 "	"	31, 1922.
"	156-159,		50 "	"	31, 1922.
"	162-172,		100 "	"	31, 1922.
"	173-186,		600 "	"	31, 1922.
"	187-190,		50 "	"	31, 1922.
"	191-222,*†		150 "	"	31, 1922.
"	223-226,		50 "	"	31, 1922.
"	227-230,		150 "	"	31, 1922.

CORRECTIONS AND INSERTIONS

Contributors to volume 33 have been invited to send corrections and insertions to be made in their papers, and the volume has been scanned with some care by the Editor. The following are such corrections and insertions as are deemed worthy of attention:

- Page 5, line 17 from top, *for* "hypothesis" *read* hypotheses
- " 14, add to the list of Fellows elected the name of R. A. LIDDLE, Austin, Texas, Associate Geologist, Bureau of Economic Geology, University of Texas.
- " 149, line 9 from top, *for* "hypotheses" *read* hypothesis
- " 178, line 24 from top, *insert* an * before the name of R. T. HILL
- " 179, line 20 from top, *insert* December, 1919, after the name of E. B. KNOFF
- " 183, line 22 from top, *for* "STONE" *read* "STOSE"
- " 184, line 13 from bottom, *insert* an * before the name of H. V. WINCHELL
- " 215, line 3 from bottom, *for* "phylogeny" *read* phylogeny
- " 357, line 1 from bottom, *for* "1.i W_p" *read* 1.1 W_p
- " 357, line 4 from bottom, *for* "V_wP" *read* V_{wp}
- " 358, line 2 from top, *for* "O.i W_p" *read* O.1 W_p
- " 367, line 22 from bottom, *for* "4" *read* 6
- " 529, line 5 from top, *take out* comma after "glaciation"
- " 530, line 2 from top, *take out* comma after the parenthesis
- " 530, line 4 from top, *take out* "1917"
- " 530, lines 1 and 2 from bottom, *transpose* footnotes 5 and 6
- " 625, line 8 from top, *for* "diaram" *read* "diagram"
- " 629, lines 7 and 8 from top, *for* "discussion" *read* "discussions"
- " 629, lines 17 and 18 from top, *for* "granits" *read* "granite"

‡ Bearing imprint [From BULL. GEOL. SOC. AM., VOL. 33, 1921.]

BULLETIN

OF THE

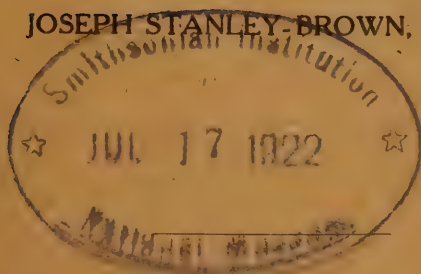
Geological Society of America

VOLUME 33 NUMBER 1

MARCH, 1922



JOSEPH STANLEY BROWN, EDITOR



PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

CONTENTS

	Pages
Proceedings of the Thirty-fourth Annual Meeting of the Geological Society of America, held at Amherst, Massachusetts, December 28-30, 1921 - - - - -	1-186
Constitution, By-Laws, and Rules of Publication - - - - -	162-172
Officers, Correspondents, and Fellows of the Society - - -	173-186
Proceedings of the Twentieth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 26, 1921 - - -	187-190
Proceedings of the Thirteenth Annual Meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921 - - - - -	191-222
Proceedings of the First Annual Meeting of the Society of Economic Geologists, held at Amherst, Massachusetts, December 28-30, 1921 - - - - -	223-226
Proceedings of the Second Annual Meeting of the Mineralogical Society, held at Amherst, Massachusetts, December 29, 1921 - - - - -	227-230
After-effects of Igneous Intrusion. Presidential Address by James F. Kemp - - - - -	231-254
Some Problems Connected with the Dakota Sandstone. Presidential Address by Timothy W. Stanton - - -	255-272

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

Subscription, \$10 per year; with discount of 10 per cent to institutions and libraries and to individuals residing elsewhere than in North America. Postage to foreign countries in the postal union, forty (40) cents extra.

Communications should be addressed to The Geological Society of America, 77th Street and Central Park, West, New York City, or care of Florida Avenue and Eckington Place, Washington, D. C.

NOTICE.—In accordance with the rules established by Council, claims for non-receipt of the preceding part of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C.,
under the Act of Congress of July 16, 1894.

Acceptance for mailing at special rate of postage provided for in Section 1103,
Act of October 3, 1917, authorized on July 8, 1918.

PROCEEDINGS OF THE THIRTY-FOURTH ANNUAL MEETING OF THE GEOLOGICAL SOCIETY OF AMERICA, HELD AT AMHERST, MASSACHUSETTS, WEDNESDAY-FRIDAY, DECEMBER 28-30, 1921.

EDMUND OTIS HOVEY, *Secretary*

CONTENTS

	Page
Session of Wednesday, December 28.....	6
Report of the Council.....	6
Secretary's report.....	6
Treasurer's report.....	9
Editor's report.....	11
Election of Auditing Committee.....	12
Election of officers.....	13
Election of Correspondent.....	13
Election of Fellows.....	14
Election of representatives on the National Research Council.....	15
Election of Committee on the Teaching of Geology.....	15
Necrology.....	15
Memorial of George Frederick Wright (with bibliography) ; by Warren Upham.....	15
Memorial of Orestes Hawley Saint John (with bibliography) ; by Charles R. Keyes.....	31
Memorial of Henry Platt Cushing (with bibliography) ; by James F. Kemp.....	44
Report of the Committee on Teaching Geology :	
Demonstration material in geology [discussion] ; by Herdman F. Cleland.....	56
Titles and abstracts of papers presented before the morning session and discussions thereon.....	86
Glaciation of New Hampshire [abstract] ; by James Walter Goldthwait.....	86
Recession of the land-ice in New England [abstract and discussion] ; by Ernst Antevs.....	86
Structure of the Connecticut basin during the Newark epoch [abstract and discussion] ; by Wilbur G. Foye.....	87
Geology of Costa Rica [abstract and discussion] ; by E. B. Branson	90
Titles and abstracts of papers presented before the afternoon session and discussions thereon.....	90

	Page
The Andean geosyncline [abstract and discussion]; by Charles Schuchert.....	90
Structural relation of the Purcell Range to the Canadian Rockies [abstract and discussion]; by Francis P. Shepard.....	91
Faults, underdrag, and landslides of the Great Basin ranges; by W. M. Davis.....	92
General morphologic features of Basin Range faults [abstract]; by George D. Louderback.....	96
Buried granite in Kansas [abstract and discussion]; by Raymond C. Moore.....	96
Intraformational corrugated rocks [abstract and discussion]; by William J. Miller.....	98
Structure of the pre-Pennsylvanian rocks of the Big Stone Gap area, Wise County, Virginia [abstract]; by George W. Stose...	98
Relation of deep-seated faults to surface structure in the region northeast of the Yellowstone Park Plateau [abstract]; by W. T. Thorn, Jr.....	99
Possible tillite at Levis, Quebec [abstract]; by Robert W. Sayles.	99
Stages of the ice age [abstract]; by Warren Upham.....	100
Glacial formations on the Coteau des Prairies [abstract and discussion]; by Frank Leverett.....	101
What constitutes the Altamont moraine? [abstract]; by Frank Leverett.....	102
Sectional meeting of Wednesday afternoon.....	104
Titles and abstracts of papers presented before the afternoon session and discussions thereon.....	104
Value of the physical characters of sand grains in the interpretation of the origin of sandstones [abstract and discussion]; by J. J. Galloway.....	104
Red limestones and their geologic significance [abstract]; by J. J. Galloway.....	105
Petrographic studies of some New York sediments [abstract]; by Harold L. Alling.....	107
Life eras before the Cambrian [abstract]; by Charles R. Keyes..	107
Quantitative study of the derivation of North American Algonkian sediments [abstract]; by Arthur C. Trowbridge and Waldo S. Glock.....	108
Cambro-Ordovician section near Mount Robson, western Canada [abstract]; by Lancaster D. Burling.....	108
Trenton of central Tennessee and Kentucky [abstract]; by Percy E. Raymond.....	109
Stratigraphy of the crystalline schists of Pennsylvania and Maryland [abstract and discussion]; by Eleanor Bliss Knopf and Anna I. Jonas.....	110
Proposed new nomenclature of the Appalachian Coal Measures [abstract and discussion]; by George H. Ashley.	111
Revision of the Paleozoic Systems. Part II: The Ordovician System [abstract and discussion]; by E. O. Ulrich.....	112

	Page
Session of Wednesday evening.....	112
Presidential address and smoker.....	112
After effects of igneous intrusion (title) ; Presidential address by James F. Kemp.....	113
Session of Thursday, December 29.....	113
Report of the Auditing Committee.....	113
Symposium on isostasy.....	113
Theory of isostasy—a geological problem [title] ; by William Bowie	113
Condition of the earth's crust and the earlier American gravity determinations [title] ; by George R. Putnam....	113
Some considerations touching on isostasy [title] ; by H. O. Wood.	114
Isostasy and earth movements [title] ; by Harry Fielding Reid...	114
Isostasy and applied geology [title] ; by James F. Kemp.....	114
Folding of mountain ranges—the argument from isostasy [title] ; by Sir Sidney Burrard.....	114
Isostatic compensation considered as a cause of thrusting [title] ; by Andrew C. Lawson.....	114
Isostasy and rock density [title] ; by Henry S. Washington.....	114
Weight of sediments per unit volume [titl] ; by Alfred C. Lane...	114
Rôle of isostatic stress [title] ; by Bailey Willis.....	114
Session of Thursday afternoon.....	115
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	115
Comparative study of the Nebraskan and Kansan tills in Iowa [abstract] ; by George F. Kay.....	115
Further data on the differentiation of the glacial drift sheets of northern Illinois [abstract and discussion] ; by M. M. Leighton.	116
Late Pleistocene history of the Lower Mohawk and Middle Hud- son region [abstract] ; by James H. Stoller...	117
Ablation of the eastern lobe of the Wisconsin ice-sheet [abstract] ; by John H. Cook.....	117
Preliminary notes on the shorelines of glacial Lake Nashua, near Fitchburg, Massachusetts [abstract] ; by Thomas C. Brown....	118
Map of the Pleistocene lakes of the Basin-and-Range province, and its significance [abstract and discussion] ; by O. E. Meinzer	118
Is the channel of the Missouri River through North Dakota of Tertiary origin? [abstract] ; by James E. Todd.....	120
Former courses of the Androscoggin River [abstract] ; by Irving B. Crosby.....	121
Peneplains and the geographic cycle ; by W. M. Davis.....	121
Retrograding of offshore bars [abstract] ; by Douglas W. Johnson	121
Rôle of crosswaves in the formation of tomboloes and points [ab- stract and discussion] ; by Roswell H. Johnson.....	122
Geology of the Colorado River in southeastern Utah [abstract] ; by C. R. Longwell, H. D. Miser, R. C. Moore, and Sidney Paige.	122
Cambrian succession of northwestern Vermont [abstract and dis- cussion] ; by Arthur Keith.....	123

	Page
Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia [abstract]; by Kenneth C. Heald and Kirtley F. Mather.....	124
Geology of Kauai, Hawaiian Islands [abstract]; by N. E. A. Hinds	125
Sectional meeting of Thursday afternoon.....	126
Tubular amygdaloid from Nova Scotia [abstract]; by T. L. Walker and A. L. Parsons.....	126
Graphic study of igneous rock series; by Frank F. Grout.....	127
Mount Monadnock, Vermont—a Monteregeian hill [abstract and discussion]; by John E. Wolff.....	127
Geology of the Pawtuckaway Mountains [abstract]; by E. S. C. Smith.....	128
Evidences of assimilation during the Katmai eruption of 1912 [abstract]; by C. N. Fenner.....	129
Tridymite-orthoclase rock, a new metamorphic rock type from Imperial County, California [abstract and discussion]; by Austin F. Rogers.....	129
Genetic features of alnoitic rocks from Isle Cadieux, Quebec [abstract]; by N. L. Bowen.....	130
Sillimanite-schist inclusions in granite [abstract]; by W. J. Miller.....	130
Preliminary notes on some regularly banded argillites which suggest seasonal deposition [abstract]; by Robert W. Sayles.....	133
Session of Thursday evening.....	134
Annual dinner.....	134
Presentation of loving cup to Prof. B. K. Emerson.....	134
Greetings from Section E, American Association for the Advancement of Science.....	135
Session of Friday, December 30.....	136
Vote of thanks.....	136
Report of the Council Committee on Policy.....	136
Titles and abstracts of papers presented at the morning session and discussions thereon.....	138
Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina [abstract and discussion] by Kirtley F. Mathe.....	138
Some astronomical tests of the planetesimal hypothesis [abstract]; by Harry Fielding Reid.....	140
Marginal belts of the coral seas [abstract]; by W. M. Davis.....	140
Transgressions, regressions, and shoreline displacements during the Pleistocene [title]; by Chester A. Reeds.....	140
Old and new standards of Pleistocene subdivision [title]; by Henry Fairfield Osborn and Chester A. Reeds.....	140
Is the present the first of a new chapter? [abstract]; by A. C. Lane.....	141
Hot springs of Lassen National Park [abstract]; by A. L. Day and E. T. Allen.....	141

	Page
Recent eruption of Lassen Peak [abstract]; by A. L. Day and E. T. Allen.....	141
Surface fusion of lava; by J. S. Diller.....	142
A source of heat in volcanic activity [abstract and discussion]; by Leason H. Adams.....	144
Use of foraminifera in determining underground structure, espe- cially in petroleum mining [abstract]; by J. A. Cushman.....	145
Session of Friday afternoon.....	146
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	146
Deccan traps and other plateau basalts [abstract]; by Henry S. Washington.....	146
Geology of the Guilford, Connecticut, quadrangle [abstract and discussion]; by Wilbur G. Foye.....	147
Jasperoid of the Joplin district, Missouri, Kansas, and Oklahoma [abstract]; by W. S. Tangier Smith.....	147
Transitional coals and their bearing on hypothesis of the origin of coals [abstract]; by Edward C. Jeffrey.....	148
Organization of Pennsylvania anthracite and the peat hypothesis of the origin of coal [abstract and discussion]; by Edward C. Jeffrey.....	149
Ore deposits of Leadville, Colorado [abstract]; by G. F. Loughlin	149
Antimony mines of Shiu Chow, China [abstract]; by George D. Hubbard.....	149
Source of the sulphates in the Salina beds [abstract]; by David H. Newland.....	150
Flooding of oil wells by fresh water [abstract]; by Thomas C. Brown.....	151
Sectional session of Friday afternoon.....	151
Titles and abstracts of papers presented at the afternoon session and discussions thereon.....	151
Oriskany of Oklahoma [abstract and discussion]; by Charles Schuchert.....	151
Age of the Talladega phyllite [abstract]; by William F. Prouty..	151
Constitution of the Ohio black shales [abstract and discussion]; by George H. Chadwick.....	152
Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama [abstract and discussion]; by Wilbur A. Nelson.....	152
Strata near Stuart, Iowa [abstract]; by John L. Tilton.....	153
Environment of the early Permian insects of Kansas [abstract and discussion]; by Carl O. Dunbar.....	153
Some cavern deposits in the Permian in west Texas; by J. A. Udden.....	153
Paleozoic-Mesozoic contact throughout Wyoming [abstract]; by S. H. Knight.....	155
Stratigraphy of the Lower Oreodon beds of the South Dakota Big Badlands [abstract and discussion]; by William J. Sinclair....	155

	Page
Discussion of the Pleistocene and its vertebrate faunas [abstract and discussion]; by Oliver P. Hay.....	156
Licks and caves of the Lower Ohio Valley as repositories of mammalian remains, including those of man; by Arthur M. Miller..	156
Correlation of the Jurassic formations of western Cuba [abstract and discussion]; by Barnum Brown and Marjorie O'Connell...	159
Register of the Amherst meeting, 1921.....	160
Constitution and By-Laws.....	162
Officers, Correspondents, and Fellows of the Geological Society of America	173

SESSION OF WEDNESDAY, DECEMBER 28, 1921

The Thirty-fourth Annual Meeting of the Geological Society of America was called to order in Williston Hall, Amherst College, Amherst, Massachusetts, at 9.30 o'clock a. m., by President James F. Kemp, who introduced President Meiklejohn, of Amherst. President Meiklejohn welcomed the Society to the college, saying that it was particularly fitting that the meeting of the Geological Society of America, the Paleontological Society, the Mineralogical Society of America, and the Society of Economic Geologists should be held in the place which had given so many leading geologists to the country, including the present and two former presidents of the parent organization.

REPORT OF THE COUNCIL

To the Geological Society of America, in thirty-fourth annual meeting assembled:

The regular annual meeting of the Council was held at Chicago, Illinois, in connection with the meeting of the Society, December 28-30, 1920. Special meetings were held in New York on April 20 and October 3, 1921.

The details of administration for the thirty-third year of the existence of the Society are given in the following reports of the officers:

SECRETARY'S REPORT

To the Council of the Geological Society of America:

The Secretary's annual report for the year ending November 30, 1921, is as follows:

Meetings.—The proceedings of the annual general meeting of the Society, held at Chicago, Illinois, December 28-30, 1920, have been recorded in volume 32, pages 1-118, of the Bulletin, and of the Paleonto-

logical Society, pages 119-156; of the Society of Economic Geologists, pages 157-162; of the Mineralogical Society, pages 163-170, of the same volume.

Membership.—During the past year the Society has lost five Fellows by death—G. Frederick Wright, H. P. Cushing, M. E. Wadsworth, Orestes H. St. John, and J. W. Spencer. The names of the thirty-four Fellows elected at the Chicago meeting who qualified have been added to the printed list. The present enrollment of the Society is 447. Twenty-two candidates for Fellowship and one for Correspondentship are before the Society for election and several applications are under consideration by the Council.

Distribution of the Bulletin.—There have been received during the year twelve new subscriptions to the Bulletin; twenty-one have not yet been renewed. The number of volumes sent out to subscribers is now 139. Five volumes are distributed gratis to the Library of Congress, the American Museum of Natural History, and the government geological surveys of the United States, Canada, and Mexico.

The irregular distribution of the Bulletin during the past year has been as follows: Complete volumes sold to public, 48; complete volumes sold to Fellows, 2; sent out to supply deficiencies, 3; sent out to supply delinquents, 7; brochures sold to Fellows, 23; sold to public, 185; sent out to supply delinquents, public, 105; sent out to supply deficiencies, public, 22; sent out to supply delinquents, Fellows, 35; sent out to supply deficiencies, Fellow, 1. Index to volumes 1-10 sold to the public, 3; Index 11-20, 2; Index 21-30, 100. Restoration of exchanges interrupted by the war: volumes, 120; brochures, 8.

Bulletin sales.—The receipts from subscriptions to and sales of the Bulletin during the past year are shown in the following table:

Bulletin Sales, December 1, 1920–November 30, 1921

	Complete volumes.			Brochures and parts.			Grand total.
	Fellows.	Public.	Total.	Fellows.	Public.	Total.	
Volume 1...		\$7.50	\$7.50				\$7.50
Volume 2...		15.00	15.00	\$3.00	\$0.55	\$3.55	18.55
Volume 3...		15.00	15.00		.90	.90	15.90
Volume 4...		15.00	15.00				15.00
Volume 5...		15.00	15.00		3.00	3.00	18.00
Volume 6...		15.00	15.00		.60	.60	15.60
Volume 7...		15.00	15.00				15.00
Volume 8...		15.00	15.00				15.00
Volume 9...		15.00	15.00	.45	.60	1.05	16.05
Volume 10...		22.50	22.50		1.30	1.30	23.80
Volume 11...		15.00	15.00				15.00
Volume 12...		15.00	15.00	.79		.79	15.79
Volume 13...		15.00	15.00	.60		.60	15.60
Volume 14...		15.00	15.00	1.80		1.80	16.80
Volume 15...		15.00	15.00	.75	1.70	2.45	17.45
Volume 16...		7.50	7.50		1.30	1.30	8.80
Volume 17...		7.50	7.50	.35	1.02	1.37	8.87
Volume 18...		7.50	7.50		.30	.30	7.80
Volume 19...				.30		.30	.30
Volume 20...		15.00	15.00		9.10	9.10	24.10
Volume 21...					.90	.90	.90
Volume 22...		15.00	15.00		2.45	2.45	17.45
Volume 23...		15.00	15.00	1.95	2.10	4.05	19.05
Volume 24...		15.00	15.00	.10	5.00	5.10	20.10
Volume 25...		15.00	15.00		1.70	1.70	16.70
Volume 26...		22.50	22.50				22.50
Volume 27...		22.50	22.50	.80	4.60	5.40	27.90
Volume 28...		32.50	32.50	11.30	31.92	43.22	75.72
Volume 29...		15.00	15.00	.55	18.63	19.48	34.48
Volume 30...	\$7.50	37.50	45.00	15.95	333.92	349.87	394.87
Volume 31...	7.50	315.00	343.50		6.55	6.55	329.05
Volume 32...		1,148.60	1,148.60		17.10	17.10	1,165.70
Volume 33...		156.00	156.00				156.00
Total....	15.00	\$2,072.10	\$2,087.10	\$38.90	\$445.24	\$484.14	\$2,571.24
Index 1-10...		11.25	11.25				11.25
Index 11-20...		10.50	10.50				10.50
Index 21-30...		312.00	312.00				312.00
Total....	15.00	\$2,405.85	\$2,420.85	\$38.90	\$445.24	\$484.14	\$2,904.99

Charged on 1920 account, but not yet received..... \$32.00

Charged on 1921 account, but not yet received..... 53.05

Total \$85.05

Receipts for the fiscal year..... \$2,904.99

Previously reported 27,074.58

Total receipts to date..... \$29,553.05

Expenses.—The following table gives the cost of administration and of Bulletin distribution during the past year:

EXPENDITURES OF SECRETARY'S OFFICE DURING THE FISCAL YEAR ENDING NOVEMBER
30, 1921

Account of Administration

Printing and stationery.....	\$178.75	
Postage	56.31	
Telegrams and telephone.....	15.00	
Group portrait.....	11.61	
Minute book.....	4.13	
Manifolding	2.00	
Sundries connected with Chicago meeting.....	9.30	
Express	.90	
Cash Book.....	1.25	
Badges	11.00	
Loss on foreign exchange.....	.37	
		\$290.80

Account of Bulletin

Postage	\$94.23	
Express	15.85	
Extra manual labor (<i>in re</i> foreign exchanges).....	25.00	
Messenger	3.20	
Telegrams	1.11	
Addressograph plates.....	1.94	
Typewriting paper.....	2.00	
Loss on foreign exchange.....	.14	
Exchange on checks.....	1.75	
Clerical hire authorized by Council.....	400.00	
		545.22

Grand total..... \$836.02

Respectfully submitted,

EDMUND OTIS HOVEY,
Secretary.

TREASURER'S REPORT

To the Council of the Geological Society of America:

The Treasurer herewith submits his annual report for the year ending November 30, 1921.

The membership of the Society at the present time is 447, of whom 360 pay annual dues. Thirty-five new members were elected at the last annual meeting, 34 of whom qualified. Two elected in 1919 also qualified, making a total of 36 new members. There have been 5 deaths

during the year, one a Life Member, which leaves the total Life Members at 87. Three members were dropped during the year for the non-payment of dues. When the books closed for the year 9 members were delinquent in the payment of dues—1 for 4 years, 2 for 3 years, 6 for two years—and are therefore liable to be dropped from the roll, and 21 for 1 year.

RECEIPTS

Cash on hand, December 1, 1920.....	\$1,774.41
Fellowship fees: 1917 (1).....	\$10.00
1918 (1).....	10.00
1919 (2).....	20.00
1920 (17).....	170.00
1921 (332).....	3,320.00
1922 (1).....	10.00
	————— 3,540.00
Initiation fees (36).....	360.00
Interest on investments.....	1,380.00
Interest on deposit in Baltimore Trust Company.....	56.02
Group portrait.....	12.00
Collection charges added to checks.....	.75
Received from Secretary:	
Sales of publication.....	\$2,904.99
Sales of group portrait.....	480.00
Postage and express.....	43.93
Author's separates.....	188.65
Author's corrections.....	3.28
Collection of checks.....	2.75
Engravers' charges.....	6.50
Printing	14.50
	————— 3,647.60
	————— \$10,770.78
	=====

EXPENDITURES

Secretary's office:	
Administration	\$319.09
Bulletin	716.98
Portrait	987.53
Salary	1,000.00
	————— \$3,023.60
Treasurer's office:	
Expenses	\$27.50
Clerk	150.00
	————— 177.50
Publication of Bulletin:	
Printing	\$5,209.36
Engraving	260.31
Editor's salary.....	250.00
	————— 5,719.67

Mineralogical Society of America.....	150.00	
H. F. Cleland, expenses of Committee on Teaching of Geology	15.05	
Balance in Baltimore Trust Company.....	1,684.96	
		————— \$10,770.78

Respectfully submitted,

EDWARD B. MATHEWS,
Treasurer.

EDITOR'S REPORT

To the Council of the Geological Society of America:

The following tables cover statistical data for the thirty-two volumes thus far issued:

ANALYSIS OF COSTS OF PUBLICATION

Cost.	Average— Vols. 1-30.	Vol. 31. *	Vol. 32.
	pp. 737. pls. 31.	pp. 468. pls. 14.	pp. 506 pls 12
Letter press.....	\$1,776.16	\$1,541.45	\$1,883.18
Illustrations.....	433.34	131.94	272.44
Paper.....	428.12	266.64	792.00
Total.....	\$2,566.03	\$1,940.03	\$2,947.62
Average per page.....	\$3.51	\$4.15	\$5.83

* When volume 31 went to press it was supposed that the price of the paper as given above was correct, but an adjustment had to be made later. The corrected figures are \$476.49, which increases the total cost of the volume to \$2,149.88 and the average price per page to \$4.57.

CLASSIFICATION OF SUBJECT-MATTER

Volume.	Areal geology.	Physical geology.	Glacial geology.	Physiographic geology.	Petrographic geology.	Stratigraphic geology.	Paleontologic geology.	Economic geol-ogy.	Official matter.	Memorials.	Unclassified.	Total.
	Number of Pages.											
1	116	137	92	18	83	44	47	---	60	4	4	593+xii
2	56	110	60	111	52	168	47	9	55	1	7	662+xiv
3	56	41	44	41	32	153	104	---	61	15	1	541+xii
4	25	134	38	74	52	52	14	---	47	32	2	458+xii
5	138	135	70	54	28	51	107	---	71	14	9	665+xii
6	50	111	75	39	71	99	1	---	63	25	4	538+x
7	38	77	105	53	40	21	123	4	66	28	13	558+x
8	34	50	98	5	43	67	58	14	79	8	---	46+x
9	2	102	138	---	44	28	64	16	64	12	---	60+x
10	35	33	96	37	59	62	68	28	84	27	17	534+xiii
11	65	110	21	10	54	31	188	7	71	60	46	651+xii
12	199	39	55	53	24	98	5	5	70	2	---	538+xi
13	125	17	13	24	28	116	42	4	165	32	29	583+xii
14	48	47	48	59	183	118	22	1	80	14	1	609+xi
15	26	124	3	94	36	267	---	---	77	17	3	636+x
16	64	111	78	30	102	141	19	---	67	22	15	636+xiii
17	49	161	41	84	47	294	27	---	71	9	2	785+xiv
18	16	164	141	5	29	246	5	---	68	40	3	717+xii
19	106	108	29	66	30	155	32	---	56	15	20	617+x
20	43	54	35	29	37	45	303	8	60	3	132	749+xiv
21	72	234	75	48	85	70	106	1	111	11	10	823+xvi
22	23	54	28	28	23	403	74	---	63	49	1	747+xii
23	75	52	126	108	19	145	134	---	66	32	1	758+xvi
24	18	57	96	57	49	160	106	23	133	53	3	737+xviii
25	34	211	54	32	156	9	175	---	108	9	22	802+xviii
26	---	72	23	11	56	90	148	---	54	44	6	504+xxi
27	1	59	125	31	146	20	271	2	73	24	5	739+xviii
28	25	273	70	69	78	209	55	39	94	110	14	1005+xxii
29	3	107	62	15	127	169	64	---	73	57	21	679+xix
30	160	3	41	9	5	36	205	16	73	59	50	644+xiii
31	1	80	19	4	13	45	22	21	69	97	79	450+xviii
32	73	47	7	27	63	51	77	17	105	2	37	488+xviii

Respectfully submitted,

JOSEPH STANLEY-BROWN, *Editor.*

The foregoing report is respectfully submitted.

THE COUNCIL.

December 28, 1921.

ELECTION OF AUDITING COMMITTEE

The printed report of the Council having been delayed, so that it was not at hand, its consideration was postponed and the Treasurer's report was referred to a duly elected Auditing Committee, consisting of Harry

Fielding Reid and Edson S. Bastin, for consideration and report at the meeting on Thursday.

ELECTION OF OFFICERS

The Secretary then reported that the following list of officers of the Society for 1922 had been elected:

*OFFICERS FOR 1922**President:*

CHARLES SCHUCHERT, New Haven, Connecticut

First Vice-President:

HENRY S. WASHINGTON, Washington, D. C.

Second Vice-President:

ROBERT T. HILL, Glendale, California

Vice-Presidents representing the affiliated societies:

W. D. MATTHEW, New York City

From the Paleontological Society

T. L. WALKER, Toronto, Canada

From the Mineralogical Society of America

Secretary:

EDMUND OTIS HOVEY, New York City

Treasurer:

EDWARD B. MATHEWS, Baltimore, Maryland

Editor:

JOSEPH STANLEY-BROWN, New York City

Councilors (1922-1924):

E. S. BASTIN, Chicago, Illinois

L. G. WESTGATE, Delaware, Ohio

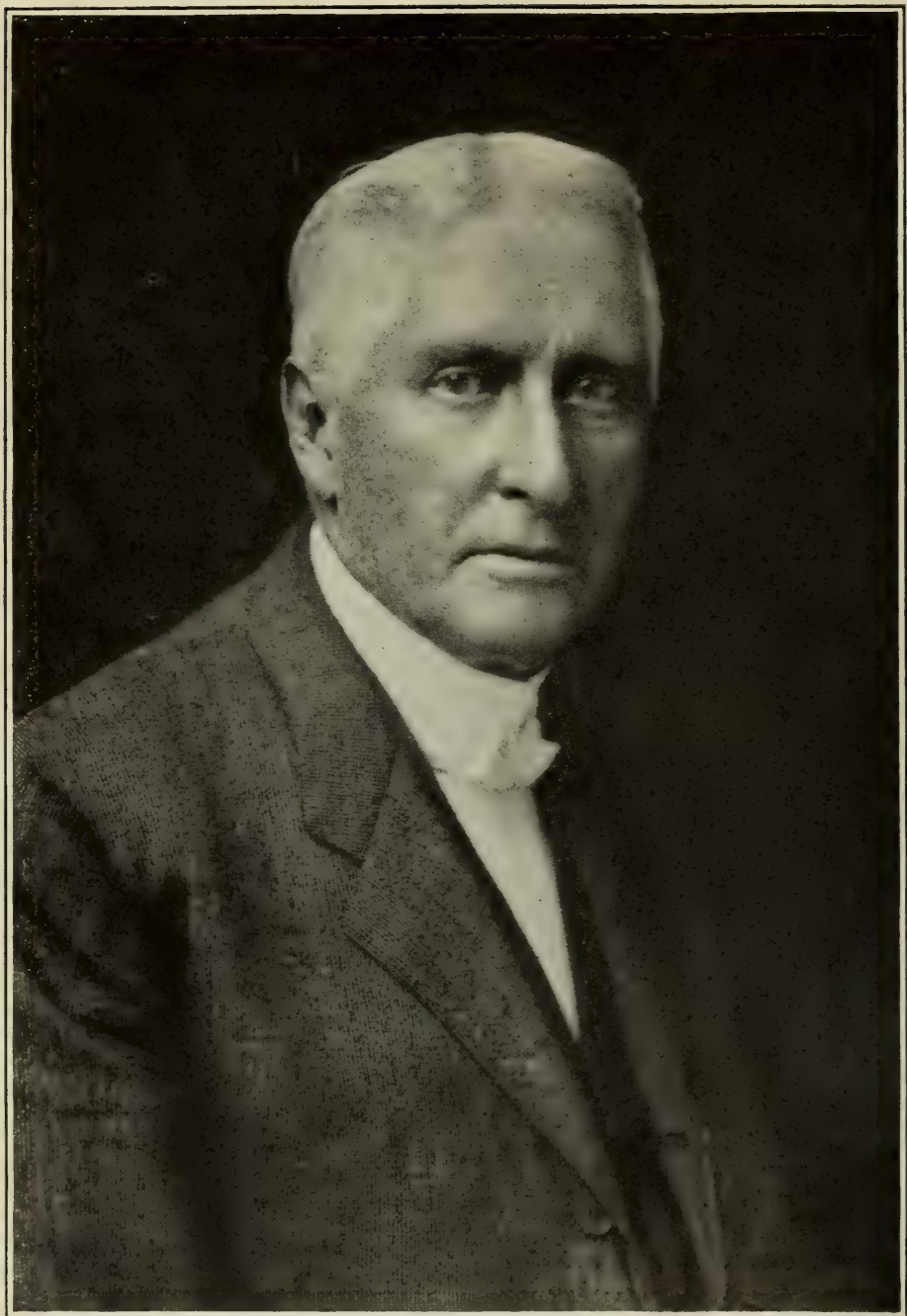
ELECTION OF CORRESPONDENT

The Secretary announced the election of EMMANUEL DE MARGERIE, Director of the Geological Survey of Alsace, as Correspondent.

ELECTION OF FELLOWS

The Secretary further announced the election of the following persons to Fellowship in the Society:

- WALTER SCOTT ADKINS, University of Texas, Austin, Texas.
- DONALD CLINTON BARTON, A. B., A. M., Ph. D., Amerada Petroleum Corporation, Houston, Texas.
- THOMAS MONTEITH BRODERICK, B. A., Ph. D., Geologist, Calumet and Hecla Mining Company, Calumet, Michigan.
- WILLIAM HENRY COLLINS, B. A., Director, Geological Survey of Canada, Ottawa, Canada.
- ALBERT WILLIAM GILES, A. B., M. S., Associate Professor of Geology, University of Virginia, Charlottesville, Virginia.
- WINIFRED GOLDRING, B. A., M. A., Assistant in Paleontology, New York State Museum, Albany, New York.
- OLIVER PERRY HAY, A. B., A. M., Research Associate, Carnegie Institution, Washington, D. C.
- FRANK L. HESS, B. A., Geologist, United States Geological Survey, Washington, D. C.
- ELBRIDGE CHURCHILL JACOBS, S. B., Professor of Mineralogy and Analytical Chemistry, University of Vermont, Burlington, Vermont.
- OLAF PITT JENKINS, A. B., M. A., Assistant Professor of Economic Geology, State College of Washington, Pullman, Washington.
- MORRIS MORGAN LEIGHTON, B. A., Assistant Professor of Geology, University of Illinois, Urbana, Illinois.
- RAYMOND CECIL MOORE, A. B., State Geologist and Head of Department of Geology, University of Kansas, Lawrence, Kansas.
- ROBERT MILTON OVERBECK, A. B., Ph. D., Associate Geologist, United States Geological Survey, Washington, D. C.
- TERENCE THOMAS QUIRKE, E. M., M. Sc., Associate Professor and Chairman, University of Illinois, Urbana, Illinois.
- JOHN BERNARD REESIDE, JR., A. B., Ph. D., Associate Geologist, United States Geological Survey, Washington, D. C.
- DOUGLAS RAMSAY SEMMES, B. A., M. A., Professor of Geology and Mineralogy, University of Alabama, University, Alabama.
- RICHARD A. SMITH, A. B., M. A., Director of Geological and Biological Survey, Lansing, Michigan.
- ABRAM OWEN THOMAS, B. Ph., M. S., Associate Professor of Geology, University of Iowa, Iowa City, Iowa.
- GERALD A. WARING, A. B., Geologist, Port of Spain, Trinidad, British West Indies.
- ROGER CLARK WELLS, A. B., Ph. D., Physical Chemist, United States Geological Survey, Washington, D. C.
- WENDELL PHILLIPS WOODRING, A. B., Geologist, United States Geological Survey, Washington, D. C.



H. Frederick Wright

ELECTION OF REPRESENTATIVES ON THE NATIONAL RESEARCH COUNCIL

Rollin T. Chamberlin and Frederick Eugene Wright were elected representatives on the advisory council of the National Research Council, to serve from July 1, 1922, to June 30, 1925, inclusive.

ELECTION OF COMMITTEE ON THE TEACHING OF GEOLOGY

H. F. Cleland, H. L. Fairchild, G. F. Kay, F. L. Ransome, W. S. Bayley, and C. P. Berkey were elected as members of the Committee on the Teaching of Geology.

NECROLOGY

The Secretary announced the death during the year of five Fellows, four of whom were original Fellows of the Society. Brief oral tributes were given as follows: Of Henry P. Cushing by James F. Kemp; of Orestes H. Saint John by the Secretary, abstracting the written memorial of Charles R. Keyes; of J. W. Spencer by E. W. Shaw; of M. E. Wadsworth by A. C. Lane; of G. F. Wright by J. B. Woodworth, following the manuscript of Warren Upham. The written memorials follow.

MEMORIAL OF GEORGE FREDERICK WRIGHT ¹

BY WARREN UPHAM

An earnest observer, thoughtful investigator, and popular author, writing for the multitude of general readers not less than for his fellow-specialists, is gratefully remembered and honored in the present memorial. Through forty-five years he has been my friend and associate in studies of the Ice Age, his earliest glacial publications being descriptive of gravel ridges, called kames and later eskers, in the vicinity of his second pastorate. During a previous ministry of ten years he had found a favorite recreation in many short excursions over the Green Mountains of Vermont and in the Adirondack region, examining carefully their drift deposits, whose origin or mode of formation was then only very imperfectly understood by geologists.

George Frederick Wright, revered pastor, teacher, glacialist, and archæologist, was born in Whitehall, New York, at the head of Lake Champlain, January 22, 1838. His grandfather, Enoch Wright, born in 1763, in Pittsfield, Massachusetts, who served near the end of the Revolutionary War in the Virginia campaign that culminated with the surrender of Cornwallis at Yorktown, was afterward a pioneer farmer in Whitehall. The father, Walter Wright, and the mother, whose

¹ Manuscript received by the Secretary of the Society December 12, 1921.

maiden name was Mary Peabody Colburn, lived on the original homestead, while five uncles and an aunt were married and settled upon adjoining farms.

In the spring of 1855 George Frederick Wright left the Whitehall home and came to Oberlin, Ohio, to enter Oberlin College, where he was graduated in the class of 1859, having met a part of his expenses by teaching in country schools each winter. Through the next three years he was a student of the Oberlin Theological Seminary, being graduated in 1862. At the beginning of the Civil War, in April, 1861, he enlisted in a company formed of Oberlin students, which was enrolled as Company C in the Seventh Regiment of Ohio Volunteers; but soon, on account of severe exposure in picket duty, he was prostrated with pneumonia, which disqualified him for further war service.

From his theological graduation, Wright was during nearly twenty years a Congregational pastor, at first for a decade in Bakersfield, a small village in the northwestern part of Vermont, and next, from 1872, for the Free Church in Andover, Massachusetts.

Thence, in 1881, he was called to the chair of New Testament Language and Literature in the Oberlin Theological Seminary, where he was a professor through twenty-six years, his department from 1892 being the Harmony of Science and Revelation. In 1907 he retired from active teaching and became a professor emeritus, receiving a Carnegie pension, with more full opportunities for research and literary work.

About two years after his coming to the professorship at Oberlin the publication of the *Bibliotheca Sacra*, a quarterly journal devoted to religion and theology, was removed thither from the theological seminary in Andover, where Wright had frequently contributed to its pages. From 1881 he was an associate editor, was advanced in 1883 to its editorial board of three members, and since 1900, with able associates and many contributors, he was its sole responsible editor.

Having returned in 1901 from a journey across Asia and Europe, he joined with some others, including his son, Frederick Bennett Wright, in establishing at the city of Washington the *Records of the Past*, begun as a monthly journal, but later issuing six numbers yearly, which continued through twelve years. This magazine, under the editorial direction of Professor Wright and his son, was "designed to bring before the public the most important facts brought out by archæological excavations and studies the world over." It was merged in 1914 with *Art and Archæology*, published by the Archæological Institute of America.

His first special studies of the drift formations, in Bakersfield, comprised a beautiful sand plain or low plateau on which that village is built, with a gravel ridge or esker marking the course of a glacial drain-

age channel that was tributary to the plain from the north. In Andover a very remarkable tract of eskers, collectively known as Indian Ridge, was found by Wright to be a part of a prolonged series of such ridges which he traced practically 25 miles. From the south edge of New Hampshire it crosses the Merrimac River* at Lawrence and continues southward through Andover, Reading, and Wakefield to Malden. He also mapped another and nearly parallel esker series, seven to ten miles farther east, crossing the Merrimac near Haverhill. Among the earliest to give the true explanation of the origin of kames and eskers, by deposition in the ice-walled channels of streams flowing from the ice-sheet when it was being melted away, Wright contributed four papers, published in 1875 to 1879 by the Essex Institute, the Boston Society of Natural History, and the Geological Survey of New Hampshire.

In 1881 Professor Wright and Henry Carvill Lewis were appointed by J. P. Lesley, Director of the Second Geological Survey of Pennsylvania, to trace the terminal moraine of the continental ice-sheet across that State. The account of this work, prepared by Lewis, forms volume Z in the elaborate series of that survey, being entitled "The Terminal Moraine in Pennsylvania and Western New York."

Through the interest and financial aid of friends in Ohio, Wright extended his exploration of the drift border through that State and Indiana to southern Illinois. In the vicinity of Cincinnati he ascertained that the ice margin covered the valley of the Ohio River along a distance of fully thirty miles, reaching several miles into Kentucky, and there spreading its till, with striated boulders, to a thickness of ten or fifteen feet at heights of about 400 to 550 feet above the river, which at Cincinnati is 450 feet above the sealevel. His report, "The Glacial Boundary in Ohio, Indiana, and Kentucky," 86 pages, with numerous maps, issued at Cleveland in 1884, is Tract 60 in the series of publications of the Western Reserve Historical Society.

An ice-dam of such area and height would hold a large and widely branching lake, having its surface 1,000 feet or more above the sea, along the valleys of the upper Ohio and its tributaries. Evidence for this Lake Ohio, as it was named by Prof. E. W. Claypole in a paper read before the Geological Society of Edinburgh and published in their Transactions in 1887, has been supplied by many observations of Wright and others, including most notably Prof. I. C. White, of Morgantown, West Virginia, in the Monongahela Valley.

This very interesting subject, which deserves further attention with detailed surveys of the valley terraces, was well reviewed by Wright in

* This river, and also the county and township named from it, are spelled Merrimack in New Hampshire; but the river and township in Massachusetts are Merrimac.—W. U.

the *Popular Science Monthly* for June, 1894. The area of Lake Ohio had been estimated as about 20,000 square miles, its depth at Pittsburgh having been not less than 300 feet. It belonged to the culmination of the Illinoian stage or epoch of the Glacial period, when this part of the ice-sheet east of the Mississippi attained its greatest thickness and extension. The duration of the Cincinnati glacial dam and lake, as for the far larger glacial lake Agassiz, was very probably no longer than a few thousand years; or perhaps only a few centuries of exceptional snowfall witnessed the maximum accumulation and advance of the edge of the great ice-field, doubtless fluctuating in its height and boundary, which obstructed the Ohio River.

Professor Wright was commissioned in 1884 by the United States Geological Survey to complete the examination and mapping of the limits of the drift in southern Illinois to the Mississippi River, with revision of previous work eastward, which led to his publication in 1890 of Bulletin Number 58, "The Glacial Boundary in Western Pennsylvania, Ohio, Kentucky, Indiana, and Illinois." The glacial lake Ohio is quite ably discussed and defended by this report, with consideration of an introduction by Professor Chamberlin in attempted refutation, whereby he claimed that the valley drift terraces fail to record the lake's existence, as it had been affirmed by Wright, I. C. White, J. P. Lesley, and others.

In 1886 Wright spent the month of August, with his classmate, Rev. J. L. Patton, and S. Prentiss Baldwin, in making a survey of the Muir glacier, at the head of Glacier Bay, in Alaska. From comparison of their observations with those of others, he wrote in 1916 as follows, noting great changes of this glacier:

"Our measurements established a rate of motion in the center of the glacier which exceeded anything found elsewhere outside of Greenland. Moreover, we collected evidence that the front of the glacier had withdrawn more than twenty miles in the hundred years which had elapsed since Vancouver visited the region, in the latter part of the eighteenth century. My inferences on this point were amply sustained by Prof. H. F. Reid, who studied the glacier and the region round about four years after my visit. Moreover, from surveys made twenty-five years later, it appeared that the recession of the front has continued at about the same rate which we had inferred for the previous century. In 1909 the front was seven miles and a half farther back than it was in 1886, when my photographs were made, while the surface had been lowered, by melting, 700 feet. These facts, as they become known and appreciated, cannot help having great influence in modifying current theories about the time which has elapsed since the ice retired from the glaciated area in the United States and Canada."

On his return from the Muir glacier, Wright was invited to give a course of eight lectures before the Lowell Institute in Boston, which,

after revision and enlargement for publication in 1889, formed a book of 622 pages, entitled "The Ice Age in North America and its Bearings upon the Antiquity of Man." The fifth edition, enlarged to 763 pages, was issued in 1911, and the sixth edition in 1920, with an added preface of 26 pages.

During the summer and early autumn of 1892 Professor Wright, again accompanied by Prentiss Baldwin, visited the glaciers of the Alps and examined many localities of archæological interest in France, Belgium, and southern England. Late in that year he published "Man and the Glacial Period," 385 pages, as volume 69 in the International Scientific Series of D. Appleton and Company. The part treating of the ancient glaciers of Great Britain was contributed by Prof. Percy F. Kendall, of England, and an appendix on "Tertiary Man," by Prof. Henry W. Haynes.

In 1894, with an excursion party in the steamship *Miranda*, Wright visited southern Greenland and expected to reach Disco Bay and Jacobs-havn, but an irreparable damage to the *Miranda*, by running upon a reef near Sukkertoppen, caused the expedition to be abandoned, with rescue and return in a small fishing schooner. Two years later he published "Greenland Icefields and Life in the North Atlantic," 407 pages, including collaboration by the writer of this memorial, who supplied chapters on the flora and fauna of Greenland, its inland ice-sheet, and the causes of the Ice Age.

His second course of Lowell Institute lectures, in March, 1892, was on the "Origin and Antiquity of Man," which was chosen as the title of his latest book devoted to these subjects, published in 1912 by the Bibliotheca Sacra Company.

In addition to the extensive journeys in the United States, Canada, Alaska, and Greenland, Professor Wright also made four visits to Europe, for increase of his knowledge in glacial geology and archæology. The first was in 1892, as before noted; the second, on a tour through Asia and westward around the world, in 1900 and 1901; the third in 1905, and the fourth in the autumn and winter of 1907 and 1908. His observations and researches during these travels are in part narrated, with a very interesting review and reminiscences from childhood to the age of nearly eighty years, in the "Story of My Life and Work," 459 pages, published in 1916.

From the circuit of the world, accompanied by his son and aided by him in the authorship, came two volumes in 1902, entitled "Asiatic Russia," in 637 pages, with numerous maps and other illustrations. The autobiographic "Story" gives its longest chapter, of 149 pages, to an

excellent account of his tour through Japan, northeastern China, Siberia, and Turkestan, which supplied conclusive evidence that during the Glacial period northern and central Asia had no ice-sheets. Glaciers there did not descend to the plains north of the Tian-Shan Mountains, although they are much higher and more massive than the Alps of Europe and are in the same latitude.

Two other books by Wright, among his many contributions in the fields of religious and theological literature, should be here mentioned for their chapters on Prehistoric Man and the Ice Age, namely, "Studies in Science and Religion," 390 pages, published in 1882, and "Scientific Confirmations of Old Testament History," 432 pages, in 1906.

His most noteworthy investigations in glacial geology relate to the unity and continuity of the Ice Age, on which he presented two important papers in the *American Journal of Science*, for November, 1892, and March, 1894. These dissent from the views that were prominently held by James Geikie and other glacialists, following a theory advocated by Croll, that astronomic conditions bore a large part in the causation of the Ice Age, dividing it into alternating glacial and interglacial epochs. With all the complexity of the drift formations in Europe and in North America, attesting very considerable variations in the extent of ice-sheets, it now seems well nigh certain that the Pleistocene glaciation of both continents was continuous on great central areas, although attended with occasional broad fluctuations of the ice boundaries.

Closely linked with the foregoing are other questions to which Wright likewise gave constant attention throughout his comprehensive glacial and archæologic researches. What was the duration of the Glacial period? When were the ice-sheets finally melted away? To what antiquity do the drift deposits bear testimony of man's presence?

In accordance with the time ratios of the great geologic eras, as estimated by Dana, Walcott, Wallace, and others, Professor Wright's acceptance of their conclusions, that plant and animal life began probably no longer ago than a hundred million years, must restrict the Ice Age and the existence of mankind to about one or two hundred thousand years. By his latest estimates, however, Wright deemed it improbable that even fifty thousand years have passed since the advent of man and the beginning of continental glaciation. From measurements of the rates of erosion and recession of the Saint Anthony Falls and of Niagara Falls, he coincided with N. H. Winchell and G. K. Gilbert in assigning about seven thousand years as the post-Glacial period, since the melting of the ice border upon Minnesota and the region of the Great Lakes. More recently the careful surveys of Baron De Geer in Sweden have well

demonstrated a similar geologically short period for the departure of the latest portion of the European ice-sheet, since its border was melted back from the basin of the Baltic Sea.

Many localities or districts testifying of prehistoric man in the United States were thoroughly studied by Professor Wright, including the Delaware River valley in the vicinity of Trenton, New Jersey, also at Claymont, in the northeast corner of Delaware, and numerous places in Ohio, Indiana, Kansas, Missouri, Nebraska, Minnesota, Idaho, and California. In New Jersey and Minnesota the valley drift beds yielding human relics belong to the latest, or Wisconsin, stage of glaciation, which is conspicuously marked by prolonged belts of knolly and ridged marginal moraines. Discoveries of stone implements in drift terraces of river valleys in Ohio and Indiana and of human bones and implements in the Missouri Valley loess prove that man was there somewhat earlier in the Ice Age. His greatest ascertained antiquity in America, so far as it is determined by relationship with glaciation, is shown by Wright to be at Claymont, in Delaware, giving evidence of man's presence on this continent probably as long ago as in western Europe.

At the first annual meeting of the Ohio State Archæological and Historical Society, in 1886, Professor Wright read a paper on the "Relation of the Glacial Period to Archæology in Ohio." Thenceforward through his life he was an active member of that society, was its president twelve years, from 1907 to 1919, and later served as president emeritus.

In the Geological Society of America he was an original Fellow, from its organization, in 1888, and contributed to it numerous papers from 1890 to 1918. He was also a member of the American Anthropological Association, the American Association for the Advancement of Science, the Boston Society of Natural History, the Western Reserve Historical Society, the Mississippi Valley Historical Association, and an honorary member of the Minnesota Historical Society.

Brown University conferred upon him in 1887 the honorary degree of Doctor of Divinity and Drury College, in the same year, gave him that of Doctor of Laws.

He was married, August 28, 1862, to Huldah Maria Day, who died in July, 1899. Their four children, each yet living, are all graduates of Oberlin College, namely, Mary Augusta (the wife of Dr. A. A. Berle); Etta Maria, literary assistant of her father; Frederick Bennett, during twelve years editor of *Records of the Past*; and Helen Marcia, also in literary work and in social service. He was again married, September 22, 1904, to Florence Eleanor Bedford, who survives him, residing in Oberlin.

The vigorous health of Professor Wright, which had enabled him to perform his great services as a Christian minister and teacher, and additionally to engage in much field-work and extensive travels for observations in glacial geology and archæology, with unremitting industry in authorship and editorial duties, continued almost to the end of his life. After an illness of five weeks of cardiac asthma, he died at his home in Oberlin, April 20, 1921. He was the most distinguished American clergyman and theologian who has won eminence also as an investigator and educator in the natural sciences, especially in his chosen field, where geology and anthropology unveil the primitive earliest view of the yet progressing creation of man "in the image of God."

His place of burial, in the Westwood Cemetery of Oberlin, is marked by a large boulder of a peculiar conglomerate, containing little fragments of red jasper, from its area in Canada north of Lake Huron. Several smaller boulders of the same rock formation, borne thence southward across Ohio during the Ice Age, were found by Professor Wright near the farthest limit of the glacial drift in Kentucky, having been transported by early Patrician ice-currents athwart the later southwestward courses of the Illinoisan and Wisconsin glaciation. So his body is at rest beneath a formerly ice-borne rock, as that of Louis Agassiz at Mount Auburn reposes under a mighty boulder brought from a glacier of the Swiss Alps, each awaiting the last Easter morn.

From a list of his published papers and reviews, in pages 437 to 459 of Wright's "Story of my Life and Work," the following references are mainly transcribed, with later citations since 1916; but only the titles relating definitely to geology, prehistoric archæology, and the origin and antiquity of man are here included. References are also added for books of his authorship on these subjects.

BIBLIOGRAPHY

1873. Recent works on prehistoric archæology. *Bibliotheca Sacra*, volume XXX, pages 381-384.
1875. Indian Ridge and its continuations. *Bulletin of the Essex Institute*, volume VII, pages 165-168.
1876. Some remarkable gravel ridges in the Merrimac Valley. *Proceedings of the Boston Society of Natural History*, volume XIX, pages 47-63.
Book reviews, in the *Bibliotheca Sacra*, volume XXXIII: The Great Ice Age and its Relation to the Antiquity of Man, by James Geikie; *Darwiniana*, by Asa Gray.
1878. Kames in the south part of Rockingham County [N. H.] and in northeastern Massachusetts. *New Hampshire Geological Survey*, volume III, pages 167-170, with three maps.

1879. Kames and moraines of New England. *Proceedings, Boston Society of Natural History*, volume XX, pages 210-220.
 Book reviews, *Bibliotheca Sacra*, volume XXXVI: *Elements of Geology*, by Joseph Le Conte; *Evolution of Man*, by E. Haeckel; *Darwinism and Other Essays*, by John Fiske.
1880. Man and the Glacial period. *The Independent*, March 4.
 Palæolithic man in New Jersey. *The Independent*, December 16.
 Prehistoric Andover. In *Historical Sketches of Andover, Massachusetts*, 8 pages, with maps.
 Book reviews, *Bibliotheca Sacra*, volume XXXVII: *Natural Science and Religion*, by Asa Gray; *Preadamites*, by Alexander Winchell; *Early Man in Britain*, by W. Boyd Dawkins.
1881. An attempt to estimate the age of the palæolithic-bearing gravels in Trenton, New Jersey. *Proceedings, Boston Society of Natural History*, volume XXI, pages 137-145.
 Book reviews, *Bibliotheca Sacra*, volume XXXVIII: *Creation and Early Development of Society*, by J. H. Chapin; *Essays on Art and Archæology*, by C. T. Newton; *Island Life*, by A. R. Wallace; *Anniversary Memoirs of the Boston Society of Natural History*.
1882. *Studies in Science and Religion*. Andover, Warren F. Draper; xvi, 390 pages, 4 illustrations, 5 maps. Chapter VI, pages 256-350, is "An essay on prehistoric man," with much consideration of the Ice Age.
 Book reviews, *Bibliotheca Sacra*, volume XXXIX: *Primitive Industry*, by C. C. Abbott; *Report upon the United States Geographical Surveys West of the One Hundredth Meridian*, by F. W. Putnam.
1883. Prehistoric man in North America. *The Advance*, November 8, 15, 29; December 13, 27.
 Recent investigations concerning the southern boundary of the glaciated area of Ohio. *American Journal of Science*, volume XXVI, pages 44-56.
1884. Glacial boundary in Ohio, Indiana, and Kentucky. *Western Reserve Historical Society, Tract 60*; 86 pages, 15 maps. An appendix presents a list of the bearings of glacial striæ and grooves in Ohio, pages 77-80, compiled by Col. Charles Whittlesey, and a paper entitled "Effects of the glacial dam at Cincinnati along the upper basin of the Ohio," pages 81-86, by Prof. I. C. White.
 Glacial boundary in Ohio. *Geological Survey of Ohio*, volume V, pages 750-772.
 Glacial man in Ohio. *Howe's Historical Collections of Ohio*, volume I, pages 90-99.
 Glaciated area of North America. *American Naturalist*, volume XVIII, pages 755-767.
 Niagara Gorge as a chronometer. *Bibliotheca Sacra*, volume XLI, pages 369-376.
 Prehistoric man in North America. *The Advance*, January 3, 17, 31; February 14, 28; March 13, 27; April 10, 24; May 15.
 Theory of a glacial dam at Cincinnati and its verification. *American Naturalist*, volume XVIII, pages 563-567.

1885. Man and the Glacial period in America. Magazine of Western History, volume I, pages 289-300.
1886. Wonders of Alaska. The Advance, November 11, 25; December 9.
1887. Age of the Ohio gravel beds. Proceedings, Boston Society of Natural History, volume XXIII, pages 427-436.
- Genesis and science. The Congregationalist, February 24.
- Importance of the study of the archaeology of Ohio. Ohio Archaeological and Historical Society Quarterly, volume I, pages 55-60.
- Muir glacier. American Journal of Science, volume XXXIII, pages 1-18.
- Notes on the glaciation of the Pacific coast. American Naturalist, volume XXI, pages 250-256.
- Relation of the Glacial period to archæology in Ohio. Ohio Archæological and Historical Society Quarterly, volume I, pages 174-186.
- Wonders of Alaska. The Advance, January 20, 27; March 24.
1888. Age of the Philadelphia red gravel. Proceedings, Boston Society of Natural History, volume XXIV, pages 152-157.
- Report on the present condition of mounds and earthworks of Ohio. Ohio Archæological and Historical Society Quarterly, volume I, pages 341-348.
1889. The Ice Age in North America and its bearings upon the antiquity of man. New York, D. Appleton and Company; first and second editions, xviii, 622 pages; 143 illustrations, including 37 maps; with an appendix, Probable Causes of Glaciation, by Warren Upham, pages 573-595.
- The Glacial period and Noah's deluge. Bibliotheca Sacra, volume XLVI, pages 466-474.
- Re-examination of Darwin's theory of coral islands. Bibliotheca Sacra, volume XLVI, pages 377-381.
1890. An archaeological discovery in Idaho. Scribner's Magazine, volume VII, pages 235-238.
- Discovery of a palæolithic implement at New Comerstown, Ohio. Western Reserve Historical Society, Tract 75, pages 163-176, with four plates. An account of the discovery is contributed by W. C. Mills, and a report on the genuineness and age of the implement by Prof. Henry W. Haynes, as read by him at a meeting of the Boston Society of Natural History.
- The glacial boundary in western Pennsylvania, Ohio, Kentucky, Indiana, and Illinois. United States Geological Survey, Bulletin 58, pages 112, with 18 plates and figures in the text, including 11 maps. Pages 13-38 are an introduction, by Prof. T. C. Chamberlin, arguing against the supposed evidences of a glacial lake in the upper Ohio basin, held by the barrier of the ice-sheet when its border reached across the river in the vicinity of Cincinnati.
- Moraine of retrocession in Ontario. Bulletin of the Geological Society of America, volume 1, pages 544-546.
- The Nampa image: correspondence relating to its discovery, with explanatory comments, etc. Proceedings, Boston Society of Natural History, volume XXIV, pages 424-450.
- Palæolithic man in Ohio. The Nation, volume I, page 331.

1891. The Ice Age in North America. D. Appleton and Company; third edition, with Appendix C, supplementary notes, 26 pages.
 A catastrophe of the Glacial period. *The Nation*, volume LIII, pages 350-351.
 Additional notes concerning the Nampa image. *Proceedings, Boston Society of Natural History*, volume XXV, pages 242-246.
 Antiquity of man on the Pacific coast. *The Independent*, January 15.
 Lava beds of Idaho. *Scientific American*, September 19.
 Lessons from a recent volcanic eruption in California. *The Independent*, November 19.
 Man and the Glacial period. *Popular Science Monthly*, volume XXXIX, pages 314-318.
 Origin of the Yosemite Canyon. *The Independent*, February 26.
 Prehistoric man on the Pacific coast. *Atlantic Monthly*, volume LXVII, pages 501-512.
 Recent discoveries bearing on the antiquity of man. *Bibliotheca Sacra*, volume XLVIII, pages 298-309.
 Supposed interglacial shell-beds in Shropshire, England. *Bulletin of the Geological Society of America*, volume 3, pages 505-508.
 Table Mountain archæology. *The Nation*, volume LII, pages 419-420.
 Book review, *Bibliotheca Sacra*, volume XLVIII: *Elements of Geology*, by Joseph Le Conte.
1892. Man and the Glacial Period. New York, D. Appleton and Company, in the *International Scientific Series*, Number 69; xvi, 385 pages, 108 illustrations, including 31 maps; with a paper on the glaciation of the British Isles, by Prof. Percy F. Kendall, pages 137-181, and an appendix, *Tertiary Man*, by Prof. Henry W. Haynes, pages 365-374. A second edition was issued in 1894, with a preface (pages vii-xxi) replying to criticisms.
 An English glacial myth. *The Nation*, volume LIV, pages 318-319.
 Changes in Muir glacier. *The Independent*, May 26.
 Excitement over glacial theories. *Science*, volume XX, pages 360-361.
 Extra-morainic drift in the Susquehanna, Lehigh, and Delaware valleys. *Proceedings, Philadelphia Academy of Natural Sciences*, pages 469-484.
 Geological time. *The Congregationalist*, August 4.
 Man and the Glacial period. *The Dial*, December 16.
 Man and the Glacial period. *Science*, volume XX, pages 275-277.
 Outlets to the Great Lakes. *The Nation*, volume LV, pages 217-219.
 Pre-Niagara period of the Great Lakes. *The Independent*, November 10.
 Saint Elias glacial fields. *The Nation*, volume LIV, pages 48-49.
 Supposed post-glacial outlet of the Great Lakes through Lake Nipissing and the Mattawa River. *Bulletin of the Geological Society of America*, volume 4, pages 423-427.
 Theory of an interglacial submergence in England. *American Journal of Science*, volume XLIII, pages 1-8.
 Unity of the Glacial epoch. *American Journal of Science*, volume XLIV, pages 351-373.

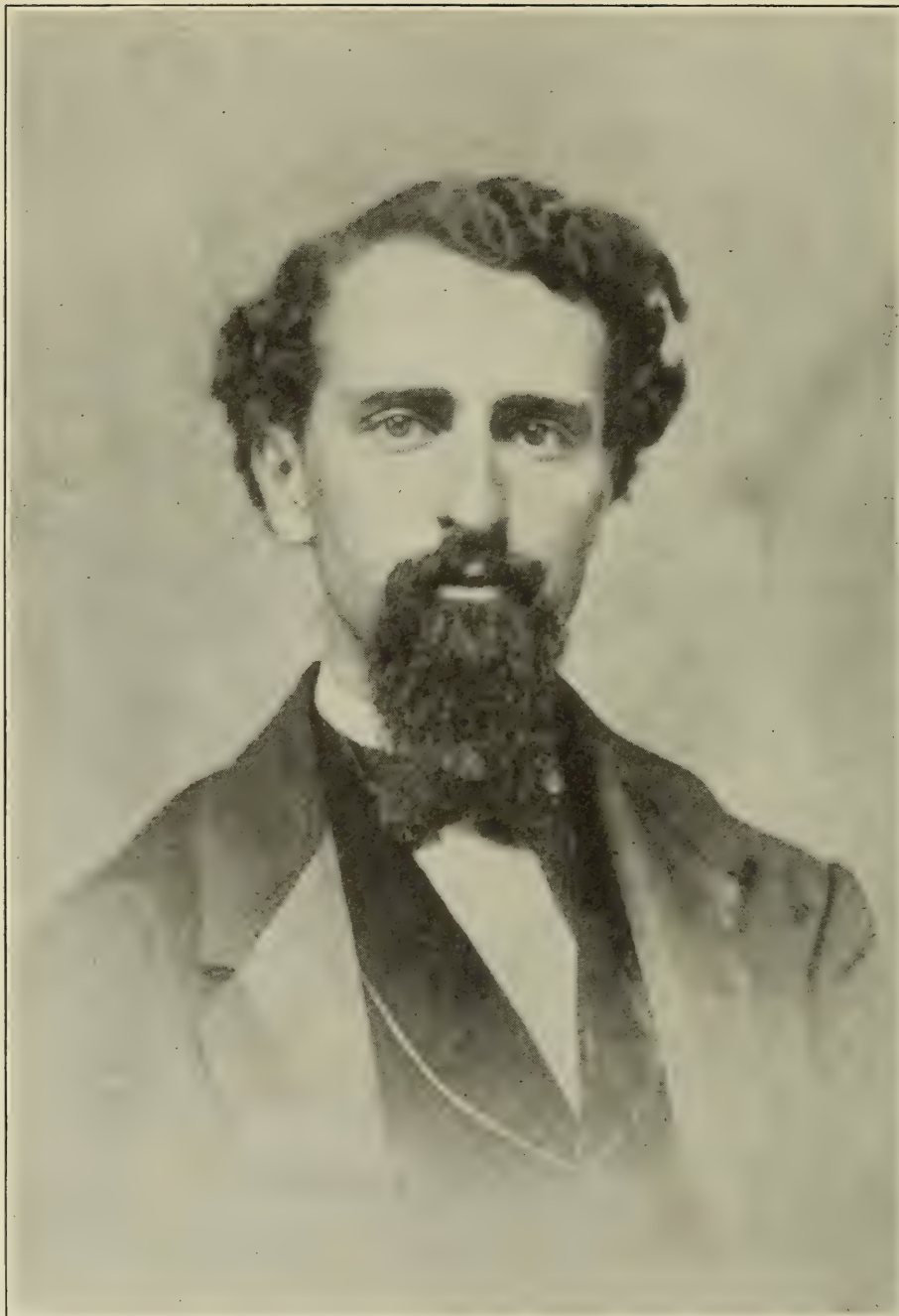
1893. Additional evidence bearing upon the Glacial history of the upper Ohio Valley. *American Geologist*, volume XI, pages 195-199.
 Commerce of the mound builders. *The Independent*, November 16.
 Evidences of Glacial man in Ohio. *Popular Science Monthly*, volume XLIII, pages 29-38.
 Glacial man in America. *The Independent*, March 30, April 13.
 Glaciers of Alaska. *Worthington's Magazine*, volume I, pages 341-354.
 The Ice Age in North America. *The Dial*, January 16.
 Mr. Holmes's criticism upon the evidence of Glacial man. *Science*, volume XXI, pages 267-268.
 Some detailed evidence of an Ice Age man in eastern America. *Science*, volume XXI, pages 65-66.
 Some of Professor Salisbury's criticisms on "Man and the Glacial Period." *American Geologist*, volume XI, pages 121-126.
1894. The Cincinnati ice dam. *Popular Science Monthly*, volume XLV, pages 184-198.
 Continuity of the Glacial period. *American Journal of Science*, volume XLVII, pages 161-187.
 Geological time. *The Independent*, April 5.
 In the Snake River valley. *Worthington's Magazine*, volume III, pages 227-241.
 Last trip of the *Miranda*. *The Congregationalist*, September 13.
 Life in the north Atlantic. *The Nation*, volume LIX, pages 422-423.
 Some remarkable fossil fish in Ohio. *The Independent*, January 4.
1895. Glacial phenomena between Lake Champlain, Lake George, and Hudson River. *Science*, new series, volume II, pages 673-678.
 Dr. Holst on the continuity of the Glacial period. *American Geologist*, volume XVI, pages 396-399.
 Geological history of Lake George. *The Independent*, November 28.
 New evidence of Glacial man in Ohio. *Popular Science Monthly*, volume XLVIII, pages 157-165.
 Observations upon the glacial phenomena of Newfoundland, Labrador, and southern Greenland. *American Journal of Science*, volume XLIX, pages 86-94.
 Book review, *Bibliotheca Sacra*, volume LII: *Manual of Geology*, by J. D. Dana.
1896. Greenland Icefields and Life in the North Atlantic, with a new discussion of the causes of the Ice Age. New York, D. Appleton and Company; xv, 407 pages, 66 illustrations in the text, 5 inset maps, including chapters VIII to XIV, by Warren Upham, pages 188-361. (Published also in London by Kegan Paul, Trench, Trübner and Company.)
 The Ice Age in North America. D. Appleton and Company. Fourth edition, with new preface, v-xxv pages.
 Age of the Philadelphia brick clay. *Science*, new series, volume III, pages 242-243.
 Fresh relics of Glacial man at the Buffalo meeting of the American Association for the Advancement of Science. *American Naturalist*, volume XXX, pages 781-784.
 The latest concerning Niagara Falls. *The Independent*, September 17.

1897. Archæological discoveries made in the gravels at Trenton, New Jersey. *Science*, new series, volume V, page 586.
 Genesis and geology. *Bibliotheca Sacra*, volume LIV, pages 570-572.
 Geology of the Yukon River. *The Independent*, August 19.
 Prehistoric man at Trenton. *The Independent*, September 9.
 Special explorations in the implement-bearing deposits on the Lalor farm, Trenton, New Jersey. *Science*, new series, volume VI, pages 637-645.
 Yukon gold fields. *The Nation*, volume LXV, pages 105-106.
1898. Agassiz and the Ice Age. *American Naturalist*, volume XXXII, pages 165-171.
 First chapter of Genesis and modern science. *Homiletic Review*, volume XXXV, pages 392-399.
 Glacial observations in the Champlain-Saint Lawrence Valley. *American Geologist*, volume XXII, pages 333-334.
 Present aspects of the questions concerning the origin and antiquity of the human race. *Protestant Episcopal Review*, volume XI, pages 300-324.
 Probable rapidity of man's early development. *Bibliotheca Sacra*, volume LV, pages 359-360.
1899. New method of estimating the age of Niagara Falls. *Popular Science Monthly*, volume LV, pages 145-154.
 Truth about the Nampa figurine. *American Geologist*, volume XXIII, pages 267-272.
1900. Archæological discoveries in Ohio. *Journal of the Archæological Institute of America*, volume IV, page 165.
 Lake Baikal to the Yenisei. *The Nation*, volume LXXI, page 267.
 Notes on Japan. *The Nation*, volume LXX, pages 395, 415-416.
 Prehistoric remains in Japan. *Science*, new series, volume XI, pages 990-991.
 Remarks on the loess in north China. *Science*, new series, volume XII, pages 71-73.
1901. Across Asia. *The Independent*, volume LIII, pages 772-775.
 Biblical and geological chronology. *The Advance*, August 29.
 Geology and the deluge. *McClure's Magazine*, volume XVII, pages 134-139.
 Geology of China. *Science*, new series, volume XIII, pages 1029-1030.
 Geology's witness to the flood. *Sunday School Times*, July 6.
 Great Jordan fault. *The Nation*, volume LXXII, pages 250-252.
 Oil fields of Baku. *The Nation*, volume LXXII, pages 46-47.
 Origin and distribution of the loess in northern China and central Asia. *Bulletin of the Geological Society of America*, volume 13, pages 127-138.
 Recent geological changes in northern and central Asia. *Quarterly Journal of the Geological Society*, London, volume LVII, pages 244-250.
 Trans-Caspian region and its evidences of the flood. *The Independent*, volume LIII, June 13, pages 1361-1363.

1902. Asiatic Russia. New York, McClure, Phillips and Company. Two volumes; xxii, 1-290; xii, 291-637 pages, 83 illustrations, 9 maps. Chapter XXVII, The Climate, in pages 517-531, is by Frederick Bennett Wright.
- Archæological interests in Asiatic Russia. Records of the Past, volume I, pages 7-14.
- Geological confirmations of the Noachian deluge. Bibliotheca Sacra, volume LIX, pages 282-293, 537-556, 695-716.
- Geology's testimony to Israel's crossing the Jordan. Sunday School Times, September 27.
- Influence of the geography of central Asia upon the early history of mankind. Transactions, Ohio College Association.
- Rate of lateral erosion at Niagara. American Geologist, volume XXIX, pages 140-143.
1903. Age of the Lansing skeleton. Records of the Past, volume II, pages 119-124.
- Another glacial wonder. The Nation, volume LXXVII, pages 461-462.
- Archæological interests of central Asia. Proceedings of the Archæological Institute of America, pages 29-31.
- Evidence of the agency of water in the distribution of the loess in the Missouri Valley. Bulletin of the Geological Society of America, volume 15, pages 575-576.
- Glacial man. Records of the Past, volume II, pages 259-271.
- The Lansing skull and the early history of mankind. Bibliotheca Sacra, volume LX, pages 28-32.
- Revision of geological time. Bibliotheca Sacra, volume LX, pages 578-582.
- Signs of the Glacial period in Japan. Science, new series, volume XVII, pages 349-350.
1904. The bone cave of San Ciro, Sicily. Records of the Past, volume III, pages 216-219.
- Evidence of the agency of water in the distribution of the loess in the Missouri Valley. American Geologist, volume XXXIII, pages 205-222.
- Geological confirmation of the flood. Homiletic Review, volume XLVII, pages 256-262.
1905. Albert Allen Wright. [Biographic memorial, with portrait, of the late professor of geology in Oberlin College.] American Geologist, volume XXXVI, pages 65-68.
- Ancient gorge of Hudson River. Records of the Past, volume IV, pages 167-171.
- Archæological notes from Sweden. Records of the Past, volume IV, pages 329-333.
- Archæological notes on northern England. Records of the Past, volume IV, pages 312-314.
- Contributions of geology to the credibility of the flood. Bible Student and Teacher, volume III, pages 11-15.
- Geological confirmation of the biblical history of Israel from Abraham to the Exodus. Bible Student and Teacher, volume II, pages 423-430.

1905. Glacial movements in southern Sweden. *American Geologist*, volume XXXVI, pages 269-271.
Physical conditions in North America during man's early occupancy. *Records of the Past*, volume IV, pages 15-26.
Professor Shimek's criticism of the aqueous origin of loess. *American Geologist*, volume XXXV, pages 236-240.
Recent date of lava flows in California. *Records of the Past*, volume IV, pages 195-198.
Book review, *Bibliotheca Sacra*, volume LXII: Central Asia and Tibet, by Sven Hedin.
1906. Scientific confirmations of Old Testament history. Oberlin, *Bibliotheca Sacra* Company, xviii, 432 pages, 32 illustrations, 8 maps. Chapters VII to XI, pages 198 to 367, contain discussions of the Glacial period. A second edition, 1907, has 434 pages.
Cedars of Lebanon. *Records of the Past*, volume V, pages 195-204.
Geology and Genesis on the creation. *Sunday School Times*, January 6.
Lebanon glacier. *Bulletin of the Geological Society of America*, volume 18, pages 637-640, with 7 illustrations from photographs.
Light from geology upon the crossing of the Red Sea by the children of Israel. *Records of the Past*, volume V, pages 295-302.
Submerged trees of the Columbia River. *Records of the Past*, volume V, pages 243-248.
Book review, *Bibliotheca Sacra*, volume LXIII: Geology, volume III, by Chamberlin and Salisbury.
1907. Recent geologic changes as affecting theories of man's development. *American Anthropologist*, new series, volume IX, pages 529-532.
1908. Chronology of the Glacial epoch in North America. *Quarterly Journal of the Geological Society*, London, volume LXIV, pages 149-151.
Fort Ancient [prehistoric earthwork in Ohio]. *Records of the Past*, volume VII, pages 191-198.
Influence of the Glacial epoch on the early history of mankind. *Records of the Past*, volume VII, pages 22-37; also *Transactions of the Victoria Institute*, London, volume XL, pages 51-76.
Latest concerning prehistoric man in California. *Records of the Past*, volume VII, pages 183-187.
New serpent mound in Ohio and its significance. *Records of the Past*, volume VII, pages 220-232.
1909. New serpent mound in Ohio. *Ohio Archæological and Historical Society Quarterly*, volume XVIII, pages 1-12.
Variations of glaciers. *Records of the Past*, volume VIII, pages 113-117.
1911. The Ice Age in North America. Oberlin, Ohio, *Bibliotheca Sacra* Company; fifth edition, much revised and enlarged, xxi, 763 pages, 196 illustrations in the text, 50 maps, 10 plates from photographs. Parts of three chapters are by Warren Upham, on Lake Agassiz (pages 401-406, with a map), Probable causes of glaciation (pages 497-525), and late Glacial quartz implements at Little Falls, Minnesota (pages 654-666, with a map).
Computing age of gravel terraces. *Records of the Past*, volume X, pages 332-333.

1911. Glacial man at Trenton. Records of the Past, volume X, pages 273-282.
1912. Origin and Antiquity of Man. Oberlin, Bibliotheca Sacra Company; xx, 547 pages, 42 illustrations, including 11 maps.
Postglacial erosion and oxidation. Bulletin of the Geological Society of America, volume 23, pages 277-296, 8 illustrations, 2 maps.
1913. Age of *Pithecanthropus erectus*. Records of the Past, volume XII, pages 93-94.
Dr. Matthew on Wright's Origin and Antiquity of Man. American Anthropologist, volume XV, pages 704-706.
Recent date of the attenuated glacial border in Pennsylvania. International Geological Congress, Report of the twelfth session, Toronto and Ottawa, pages 451-453.
1914. Age of the Don River glacial deposits. Bulletin of the Geological Society of America, volume 25, pages 205-214.
Evidence of a glacial dam in the Allegheny River between Warren and Tionesta, Pennsylvania. Bulletin of the Geological Society of America, volume 25, pages 215-218.
Man and the mammoth in America. Records of the Past, volume XIII, pages 103-105.
Prehistoric flint quarries and iron workings in Sweden. Records of the Past, volume XIII, pages 82-86.
1915. See Ohio First. Oberlin, Bibliotheca Sacra Company; viii, 85 pages.
This book gives a condensed account of the geology, physical geography, archæology, and history of Ohio, with notes of many routes for travel within the State, whereby places of special significance may be visited. A second edition was issued in 1919.
1916. Story of my Life and Work. Oberlin, Bibliotheca Sacra Company; xv, 459 pages, including bibliography of the author's papers and book reviews, but not of his published books, in pages 437-459.
Geology of Lorain County, Ohio. In Standard History of this county, volume I, pages 1-12.
Muir glacier, Alaska. Society of Alaskan Natural History and Ethnology, Bulletin II.
Book reviews, Bibliotheca Sacra, volume LXXIII: Antiquity of Man, by A. Keith; Men of the Old Stone Age, by H. F. Osborn.
1917. Report of E. H. Williams on the first phase of Pennsylvania glaciation. Science, new series, volume XLVI, pages 37-39.
1918. Evidence from Alaska of the unity of the Pleistocene glacial period. Science, new series, volume XLVII, page 364.
Explanation of the abandoned beaches about the south end of Lake Michigan. Bulletin of the Geological Society of America, volume 29, pages 235-244.
1919. Charles Conrad Abbott and Ernest Volk. [Biographic memorials.] Science, new series, volume L, pages 451-453.
1920. The Ice Age in North America. Oberlin, Bibliotheca Sacra Company; sixth edition, xxi, 24, 763 pages, 210 illustrations, including 50 maps.
1921. The Preglacial outlet of Lake Erie. Science, new series, volume LIII, pages 286-287.



Orates H. Lyden

MEMORIAL OF ORESTES HAWLEY SAINT JOHN¹

BY CHARLES R. KEYES

One of the first elected fellows of our Society, Orestes Hawley Saint John really belonged to an earlier generation and found place in the third quarter of the last century. Although well past the ripe age of fourscore years at the time of his demise, he was so long retired from active service among us that few of our present fellows were personally acquainted with him. For more than 20 years he was unable to attend our meetings; yet he was our foremost authority on the fossil fishes, and his contributions in this field greatly enriched our voluminous American literature on this subject.

As a field geologist, Saint John had few equals and certainly no superiors. So keen were his observational powers in the geological direction that he was finally inveigled into deserting the purely scientific realm which he had so auspiciously entered in Brazil, Iowa, Illinois, and Kansas, and on the Hayden surveys in Idaho, Wyoming, Colorado, and New Mexico, and into expending his superior powers on the more remunerative economic aspects.

It was due mainly to the results of his really brilliant investigations in the New Mexican region that the richest coal field on the North American continent was brought into market. For more than 30 years he was retained as geologist of the company owning the largest acreage of coking coal in this country. It was a very great pity that his magnificent abilities could not have been reserved to science, pure and simple.

Saint John's penetration in the tracing, interpreting, and predicting the position and continuity of geological formations was almost uncanny. His results in these directions were of the highest order. The large amounts of capital invested and the huge industrial enterprises set in motion on the strength of his examinations and reports amply attest the basic value of good geological insight in all exploitations of mineral resources. In a very remarkable way were his predictions fully verified by subsequent operations. His was one of the most salutary lessons of our new century in mineral development. His signal success in industrial lines and the large measure of esteem with which his researches were held only demonstrated too well that there are some enlightened corporations engaged in mining that do not treat lightly the intuitive knowledge of the trained scientist.

Although our confrère gave up his own predilections and ambitions in pure science, the world may never know how large was the measure

¹ Manuscript received by the Secretary of the Society December 31, 1921.

of his efforts in bringing to the light of day that sumptuous series of monographs on the fossil crinoids by Charles Wachsmuth and Frank Springer—a monumental tribute having no near rival in the New World and perhaps not in the Old World.

Orestes H. Saint John was born at Rock Creek, Ashtabula County, Ohio, January 12, 1841, and was therefore in his eighty-first year at the time of his demise. In early childhood his father, Orestes O. Saint John, and family removed to Iowa, settling at Waterloo, in Black Hawk County. Here young Saint John attended the public schools until ready for college, when he set out for Cambridge to study under Agassiz. In 1871, after the completion of his work on the Iowa Geological Survey and his return to Cambridge, he married Mary Sophie Swift, a direct lineal descendant from Dean Jonathan Swift, famous eighteenth century English author.

As a youth in Waterloo, Orestes became intensely interested in the organic remains with which the rocks around his home abounded. Before leaving for college he had already made large and very complete collections of these fossils from the Devonian strata of the Cedar River valley. An especially fine suite of fish remains was obtained. Of these Elasmobranch teeth were extensively represented. In some way or other concerning these teeth, Saint John got into correspondence with Professor Agassiz, who was then engaged on his monumental monograph on the fossil fishes. Presumably the Iowa collector first sent some of his specimens to Cambridge for identification.

It is quite probable that young Saint John first met the great naturalist at Iowa City when the latter was lecturing before students at the State University. The first lecture was on the "Coral Reefs of Iowa City," and was delivered in the University chapel, March 7, 1864. On the day following the lecturer spoke on "Glaciers." Agassiz had a peculiar faculty of making everything so plain that all who heard him wondered that they had not known the same things before. He was never what one would call an eloquent speaker, but his oratory was altogether the conversational and didactic style.

At any rate, Agassiz soon had the Iowa youth, with his collections, in Cambridge helping him. The young enthusiast was at once set to work studying his own treasures. This led to a warm personal friendship between pupil and master, which continued to the death of the latter. On the other hand, this humble beginning and association with a great authority developed the former into the leading specialist on the ancient fishes of this country. In after years the pupil, with infinite zest, often related his first experiences and studies under his master.

The first day in the laboratory Agassiz placed some fish materials on the table before him and told the student to find out what he could about them. Student leisurely pawed over them for about an hour, until he fancied that he had learned about all there was to learn concerning the fossils and until he thought it about time for the Professor to return; but no professor appeared that day. This was repeated daily for a whole week, but apparently with no results and no encouragement from the master. Finally, on the eighth day, when Agassiz put in appearance and asked his young protégé what he had found out, the latter, now thoroughly discouraged, unwittingly inquired about certain points of resemblance between two fishes. This happened, as he afterward found out, to be a moot point in anatomy, and the Professor was all attention, and immediately started a fire of questions so rapid that the young man did not have opportunity to answer a word. The latter had made his first important discovery. Ever after, study for him was easy.

At Cambridge at this time Saint John found other young and enthusiastic naturalists in the Agassiz laboratories. Among those who afterward became famous authorities were Joel A. Allen, the ornithologist; Alpheus Hyatt, the paleontologist; Charles E. Hartt, the geographer; Edward S. Morse, Asa S. Packard, and A. E. Verrill, the zoologists, all of whom attained eminence in their special fields.

Cambridge days were busy days with young Saint John. Besides his own studies on the fossil fishes, Professor Agassiz intrusted him with important Museum affairs. For many months he was engaged on the preliminary work of a part of the general catalogue of specimens and exhibits in the Museum. This was something more than a mere enumeration of specimens. It had the special purpose in view of testing their relative importance for the progress of science. At the same time it was particularly adapted for the ready determination of their most appropriate arrangement in the Museum. In the preparation of the catalogue of the fossils from Waldron, Indiana, of which large collections had been recently received, the intent was to lead to a correct appreciation of the peculiarities of this old fauna as compared with those of the English Wenlock fauna and of the New York Niagara fauna.

In the few months immediately preceding the departure of the Thayer Expedition to Brazil, Saint John and Hartt were busy with identifying and arranging collections received from various Western States and from Nova Scotia. Saint John alone was credited on the Museum books with obtaining 13 large boxes full of western fossils.

When Saint John returned to the Museum of Comparative Zoology, after finishing his labors on the Iowa Geological Survey, in 1870, he took

up the work exactly where he had left off four years before, but with greater energy, wider knowledge, and a breadth of observation not previously possible. The arrangement of the Carboniferous fossils was quite to his liking, and a beginning was made on the fossil fishes. He now brought to the Museum his own extensive collections, which Professor Agassiz pronounced in his annual report as the "finest he had ever seen." In the Museum report for 1873 Saint John gives an extended account of the paleontological collections on which he worked.

Memory of Saint John lingered long at Harvard. Professor Shaler in particular delighted in telling jokes on him, and especially insisted that Saint John's family pronounced its name as if it were spelled *Sin-Jin*, proof positive that it was of Erin ancestry. Possibly the Shalerian brogue was not as perfect as it might have been, the Professor coming from Kentucky.

When, in the spring of 1865, Prof. Louis Agassiz planned his famous Thayer Expedition to Brazil, he chose as one of six assistants Orestes Saint John, who had been working with him for some time in the Museum of Comparative Zoology, at Cambridge. Agassiz, Saint John, and Professor Hartt, of Cornell University, constituted the geological corps. The voyage out was one of the most enjoyable imaginable. The *Colorado*, a crack new ship of the Pacific Mail Steamer Company, was going from New York around the Horn without passengers, and the vessel was placed at the disposal of the Agassiz party so far as the latter's destination. Agassiz lectured every day of the three weeks on topics relating to the journey to be. The party sailed April 1, 1865. Mrs. Agassiz kept a diary and the connected account is included in that delightful volume entitled "Journey in Brazil."

After exploring rather thoroughly the environs of Rio de Janeiro, Hartt and Saint John spent two months studying the geology along the then recently constructed Dom Pedro Segundo Railroad. Many fine rock cuts and tunnels gave excellent sections, displaying the geological structures. Saint John especially made very complete notes and maps. The general features Professor Hartt incorporated in his "Geology and Physical Geography of Brazil," which was published several years afterward.

After the completion of the work along the railroad, Professor Agassiz arranged an exploring party under charge of Saint John, which was to cross Brazil northward from Rio de Janeiro to the mouth of the Amazon River. This company left the capital on June 9, 1865. It consisted of Orestes Saint John, John A. Allen, Thomas Ward, and George Scève. The first two members mentioned were to travel together and reach the

Atlantic coast by way of the Rio São Francisco and the Rio Paranáyba, while Mr. Ward was to descend Rio Tocantins to the Amazon and Mr. Sceva was to remain for some time in the fossiliferous regions about Lagoa Sancta for the purpose of collecting. The members of the party continued together as far as Juiz de Fora. Thence they crossed the Serra do Mantiqueira to Barbacena and kept on from that place through Lagoa Durada and Prados across the Rio Carandahy to the divide separating the headwaters of the Rio Grande on the south from those of the Rio Paraopeba on the north. They crossed the latter stream just above the water-gap of the Serras of Piedade and Itatiaia, traversing the former Serra into the mountain valley in which the village of Morro Velho is situated. They thus found themselves successively in the basins of the Rio Paranáyba, the Rio de la Plata, and the Rio São Francisco, all of these streams being fed by rivulets which rise in this vicinity. On leaving the mountainous districts they continued their route through alternate campos and wooded tracts to Gequitibá, passing through Saburá, Santa Luzia, Lagoa Sancta, and Sette Lagoas.

At Lagoa Sancta Mr. Sceva remained behind to collect bones of extinct mammalia from the caves in the neighborhood. Mr. Ward separated from his companions at Barbacena. From Lagoa Sancta, Saint John and Allen kept on together to Januaria, where the latter, whose health had been failing from the time that he left Rio de Janeiro, found himself unable to prosecute the journey farther, and he resolved to strike across the country to Bahia, taking in charge the collections they had brought together thus far.

Leaving Januaria, Saint John followed the Rio São Francisco to the Villa do Barra, where he made a short stay, and then resumed his journey by land through the valley of the Rio Grande to the Villa Santa Rita, thence to Mocambo and across the highlands separating the basin of the Rio São Francisco from that of the Rio Paranáyba. At Paranaguá he remained several days and made a considerable collection in the vicinity. Thence he followed the valley of the Rio Gurugueia to Manga, one hundred and twenty leagues away.

At Manga, Saint John embarked on one of the singular river-boats made of the leaf-stalks of the Buriti palm and descended the Rio Paranáyba to the villa of San Gonçallo. Here he stayed for some time to collect, forwarding from this vicinity a considerable number of specimens, chiefly reptiles, birds, and insects. His next station was at Therezina, the capital of the province of Piahy, where he made one of the most interesting collections of the whole journey from the waters of the Rio Poty. The Poty is a tributary of the Paranáyba, into which it empties below the city.

From Therezina, Saint John proceeded to Caxias, and finally arrived in Maranhão, by the way of the Rio Itapicurú, on the 8th of January, 1866, having completed a journey of more than seven hundred leagues in seven months, over a route the greater part of which had never been examined zoologically or geologically.

On this trip his extraordinary industry in acquiring specimens is indicated by the fact that his collections numbered over 250 mammals, 125 reptiles, 1,350 fishes, 500 insects, and 1,100 crustaceans, besides quantities of other groups and rocks—upward of 5,000 specimens altogether. The labor alone of transporting these immense collections to seaport was enormous. The care and detail devoted to the description of habits, habitats, and anatomy of more than 500 species which he garnered and the taking of notes on thousands of forms which he could not carry away with him fill volumes of note-books. These notes should have been worked up and put into shape for publication immediately, at the end of the journey; but this seems never to have been done. On arrival home at the Museum other arduous and pressing duties delayed a beginning from time to time, and then he was called away to wider fields.

The geological observations which Saint John made on this Brazilian trip were many and important, and the manner in which he recorded his facts shows that he never lost sight of the general relations between the great structural features of the country through which he passed.

During the latter part of his lonely journey toward the Amazon River, Saint John had suffered from intermittent fever. When he reached Maranhão it culminated in a severe illness. A Doctor Braga took him into his own house and did not allow him to leave until he was completely restored to health. From Maranhão he then went down to Para, where he joined Professor Agassiz, who had come up the coast from Rio de Janeiro and was spending the month around the mouths of the Amazon River. In company with the Agassiz party he now returned leisurely down the coast to the capital, where a few days were spent before sailing for home. On the second day of July the return trip was begun. To the day of his death Saint John carried with him a great store of pleasant memories and vivid pictures of this journey, which thereafter enriched his life with so much tropical warmth and color.

In the meanwhile the Iowa Legislature established a State geological survey, and Dr. Charles A. White was chosen its director. Doctor White appealed to Agassiz for advice regarding the scope of the work and the personnel of the assistants. For First Deputy State Geologist, Agassiz could not suggest any name better than that of the former Iowan who had worked so well, faithfully, and brilliantly with himself. Saint John

immediately entered on his new duties in Iowa with great industry and enthusiasm.

During the four years that he was engaged thus he got out several very creditable reports—one on the Middle Coal Measures regions, which was virgin territory, and short accounts of the mineral resources and geology of fifteen counties in the western half of the State. His efforts extended much further. As Doctor White stated, Saint John was properly to be regarded joint author of the report of Northwestern Iowa, and on the Gypsum Deposits. Besides, his artistic faculties were put to wide use in the preparation of all the maps and illustrations of the two final volumes published by the Survey.

A number of minor memoirs emanated from this work. These were chiefly descriptions of new forms of fossils and mainly appeared under the joint authorship of White and Saint John.

It was during this period that he became intimately acquainted with Otto Theime, James Love, Charles Wachsmuth, Frank Springer, and other of the Burlington collectors, Amos Worthen, of Warsaw, Illinois, and the Missouri and Kansas geologists. He took all of their fish collections and gave them in return all the crinoids and other fossils which he collected.

On the completion of his duties on the Iowa Geological Survey, Saint John accepted the chair of natural history in the Iowa State Agricultural College, at Ames, then just organized. This post he held only one year, being called to Illinois by State Geologist Worthen to work up and describe the fossil fishes of that State, of which large collections had already been made. An elaborate report, accompanied by many plates, was published as volume VI of the Illinois Geological Survey.

In 1872 Saint John went back to the Museum of Comparative Zoology to continue his work with Professor Agassiz. He remained with the latter until his demise, two years later. In Cambridge he now found Wachsmuth, who was working on the fossil crinoids, beginning that investigation which a quarter of a century afterward flowered into that monumental monograph on the subject. There Saint John also continued his studies on the Illinois fossil fishes, with the result of another fine monograph, which was incorporated in volume VII of the Illinois Geological Survey.

On the death of Agassiz, Saint John removed to Topeka, Kansas; but he was soon again engaged in geological field-work on the Hayden United States Geological Surveys of the Territories, carrying on operations first in New Mexico and Idaho and then in Wyoming and Colorado.

The first investigations were on the Coal Measures of northeastern

New Mexico, where in after years he spent so many years of his life in the interests of private corporations. The report was published in volume II of the Hayden Survey bulletins, issued in 1876.

His work in Wyoming and Idaho was mainly to the south and southwest of what is now the Yellowstone National Park. The Téton Range was the principal object of inquiry. It was found to be a gigantic monoclinical block having for a nucleus metamorphic and granitic rocks. It formed a lofty, exceedingly rugged ridge, with jagged crest, which culminated in a majestic peak which was named Mount Hayden.

Among the other ranges investigated in this connection were the Gros Ventre, the Snake River, the Caraboo, and the Blackfoot Mountains. An interesting find was a series of fossils identical with those found along the Mississippi River at Burlington and Keokuk. The presence of the Mississippian rocks were thus recognized for the first time on the Pacific slope of the continental divide. The report was profusely illustrated. The beautiful outline sketches were the forerunners of Holmes's wonderful productions a few years later. When I went through this region, forty years afterward, with Saint John's drawings before me, I could not but marvel at their great beauty and accuracy.

In the following year Saint John studied the region lying to the east, chiefly the Wind River Mountains, and made an elaborate report on their geological features.

At the close of the field season in Wyoming, Saint John returned to Topeka to write up his notes. Having done this, he turned to put the finishing touches on his monograph on the Illinois fossil fishes. Then he applied himself for several years to an intensive study of the coal-bearing deposits of southeastern Kansas and the contiguous parts of the adjoining States.

When officers of the Atchison, Topeka and Santa Fé Railroad heard of his investigations they at once proceeded to engage his services in surveying the entire region with a view of selecting and locating the most desirable fuel lands for their own use and for general and industrial purposes. This investigation presented many difficulties, not a few of them seemingly unsurmountable. In this flat-lying, little dissected country natural outcrops of the coal beds were few and far between, so that the existence and depth of possible coals had to be determined largely by inference from stratal relations many, often a hundred, miles away. His locations thus made were then verified by systematic drilling over an expanse of many thousands of acres. Thus the great Girard coal field, the greatest in all Kansas, was located and opened up.

Various other important investigations were intrusted to him from

time to time by the Santa Fé Railroad and other large interests, covering parts of the country from Oklahoma to Mexico, all of which were carried out and reported on with the conscientious care and fidelity for which he was so well known and which commanded the implicit confidence of those for whom he worked. Above all, he valued his scientific reputation and sought for the unquestionable facts by which his conclusions could be demonstrated. No argument or any amount of persuasion could induce him to give an opinion which could not be easily confirmed by actual observation as opposed to mere conjecture. His clients were thus often compelled to submit to disappointment in their expectations, but with a corresponding saving in loss from unsuccessful investment.

Later Saint John went to New Mexico to investigate the coal outlook of that region. So early as 1874 he and Mr. Frank Springer had begun privately a study of this field. Then for two seasons his attention was diverted from this work because of his duties on the Hayden Surveys of the Territories. To this New Mexico investigation he returned at irregular intervals until 1891, when becoming connected with the Maxwell Land Grant Company he took it up as his opus magnum. During the five years that he was thus engaged for the Maxwell Company he made a detailed survey of the great Raton coal field as it is today known. This was his crowning achievement in applied geology.

His especial study in the Raton field was with a view of ascertaining the magnitude and possibilities of the coal reserves for large industrial enterprises in which moneyed men might safely invest their capital. This effort consumed over a dozen years of the most detailed and painstaking labor. All natural exposures were examined and mapped, prospect holes by the thousand were dug, hundreds of coal tests were made, and all this information was reduced to reports of minutest accuracy. When the Saint Louis, Rocky Mountain and Pacific Railroad was projected, two of the most expert and favorably known coal geologists of the East were brought out, and they spent three months reviewing the work. At the end of this verification they accepted his reports in every particular and declared that there was nothing more to be said. It was on the basis of his examinations and reports that this great enterprise was launched and successfully operated for a decade and a half. An unlimited future lay before it, covering, as it did, the largest tonnage of coking coal under a single ownership in the United States. After the coal rights were acquired by the railroad Saint John became its geologist, a post which he held for 25 years.

It was at Raton that I first made personal acquaintance with Saint John. It was in 1902, when I was making some private inspections in

the Raton coal field. At that time it was the stratigraphic relationships that especially interested me. A few days before I discovered that a marked plane of unconformity existed in the very middle of the coal section, which was 4,000 feet thick. This entire succession of strata had been hitherto regarded as Laramie in age. The fossils below the unconformity line were manifestly Cretaceous types, but those above seemed to be Tertiary forms. In all his observations in this region Saint John had overlooked this feature. Following the early Government explorers, he called the entire section Laramie. When the suggestion was made that the entire Laramie formation was probably missing and might be actually represented by a hiatus, it was too new for him to grasp all at once. So we went out together to some of the localities showing the unconformity to best advantage and there freely argued the question. It was a joyous jaunt, and he seemed to be fully impressed with the stratigraphical importance of the feature. Later he wrote me fully and with much enthusiasm on the probable correctness of the conception. This was many years before the Government representatives entered the field and gleaned from the coal miners, who by this time had learned to make practical use of the suggestion, that the same conditions existed. Had Saint John been permitted to gather his notes together, his report on this great coal field would have been one of the most extensive and instructive of the kind extant.

In the long stretch of work and study Saint John at length overtaxed his body, to which he seldom showed little consideration, either in the field or in the work-room. The tired machine finally broke down, and the later years of his life were spent in semi-retirement in San Diego, California, in the mild and equable climate of which he found best relief from the ailments which followed him.

When I last visited him there, a few weeks before his demise, I little suspected that the end was so near. His was a gentle passing, which event took place on the morning of July 20, 1921, after a lingering illness, the culmination of a long period of ill health that a decade before had caused his removal from the high altitudes of New Mexico to sealevel. His faithful wife, who had also long suffered from serious illness, survived him but a few days. Thus the couple, after a married life of devoted attachment of more than half a century, passed on together over the Great Divide, as they would have chosen to do had they been permitted to express preference.

Saint John's skill is not confined to the happy transcription of field observations. He is equally adept in detailed descriptions of species and specimens. The measure of his wide researches on the character and

development of Paleozoic fishes is found in the numerous memoirs which were issued in rapid succession and in the several more pretentious monographs, all of which amply testify how extensively he contributed to our knowledge of the subject. Although working so long and so far from his native State and the habitats of his materials, it is a singular coincidence that he should have found in these distant places that the main collections consisted of specimens obtained from around his old home. Through his almost uncanny skill in reconstructing these ancient organisms from merest fragments, his home State became famous the world over.

His efforts do not stop at merely pointing out the genetic relationships of the old fishes or in delineating their structures. All of his descriptions are complete, lucid, and illuminating. Few of the forms which he described need redefinition, even after the elapse of fifty years. Large numbers of forms were noted and described as new to science.

In his methods of work, Saint John was, perhaps, overcautious and possibly a little too deliberate. He worked slowly and with infinite pains to the minutest details. He was never sufficiently satisfied with any given effort to call it complete or finished. He had an insatiable appetite for more facts, or "proofs," as he termed them, of which he always wanted just a little more. For this reason his commercial reports had almost to be extracted from him by main force. He had his own methods of work and study, from which he could not easily be diverted. When once reached, his results could always be relied on with all the confidence that human care and skill could inspire. No one was ever misled by an opinion or report by him on any question founded on geological grounds. If an opinion was not demonstrated by the facts and necessary inferences, according to his own standards of accuracy, he could not be induced to give it. It was useless to try to obtain from him offhand or hurried conclusions. Hence his results, though painfully slow in being arrived at, inspired a confidence on the part of his employers which he esteemed the best reward for his labors. The fact that a "soulless" corporation, organized and operated solely for business, pensioned him with a comfortable living honorarium for more than a decade after he had become totally incapacitated physically is best evidence of the esteem in which he was held by those to whose service he devoted the best years of his later life, and also the value which they placed on his scientific work. The episode was rather a pleasing one on both sides.

When Saint John first left the purely scientific realms to enter, what he thought temporarily, the economic field, he fully intended to return at no distant date. He had extensive plans for further researches on the

fossil fishes. For this he acquired a large amount of material through his own efforts; besides, he had free access to the fine collections of Mr. Frank Springer. Although much investigation was done along this line, full consummation was not to be.

Lure of industrial geology proved too strong and too long; and before its spell was broken painful periods of illness set in in such rapid succession, and with often entire incapacity for work, that the intervals of scientific effort became fewer and fewer and farther and farther apart, until they ceased altogether. When it was finally determined that he could not probably finish this great work, similar collections of the Iowa Paleozoic fishes which had been brought together in the meanwhile were studied, described, and figured by Dr. Charles R. Eastman, another Iowa lad, and the report was published in a sumptuous volume by the Iowa Geological Survey.

It is probable that a deterring factor to Saint John's return to the strictly scientific field was the outcome of a painful accident which befell him. In an unguarded moment, when going through the dark pine forests of the Raton Mountains one evening, he struck the sharp stub of a low bough that penetrated his eye and completely blinded him for several days. Sight was entirely destroyed in the one eye, and it was long months before all danger from loss of the other eye was passed. Doubtless at sixty years the artistic hand had lost something of its early cunning, which the eye accident suddenly brought home to him, and the outlook into the future ended in discouragement. No one ever heard him complain.

Personally Saint John was a man of singular charm of character, of pure motive, and of stainless life. He was unassuming and modest to high degree, perhaps too much so for his own best interests. He made few acquaintances, and devoted himself, something after the manner of a recluse, to his scientific work, in which he found lifelong happiness. Affable, thoughtful of the comfort of others, and ever willing to advise and help whomsoever called on him for aid, he made a most delightful companion to be with in the field.

Keen to observe, quick to interpret, and an artist of no mean ability, his notes were always clear, illuminating, and pertinent. When his work was sent to the press it was invariably finished in style and arrangement and complete to the last detail. There was nothing left to chance; nor was there opportunity to misinterpret his meaning.

Saint John was not a voluminous writer, yet his contributions to knowledge were important. They all display the same painstaking effort and completeness which is seldom attained. The list of his memoirs show how wide was his knowledge.

BIBLIOGRAPHY

- Descriptions of new sub-Carboniferous and Coal Measure fossils. Transactions of the Chicago Academy of Sciences, volume I, pages 115-127, Chicago, 1867. With C. A. White.
- Preliminary notice of new genera and species of fossils. Pamphlet, 4 pages, Iowa City, 1867. With C. A. White.
- Report of the Assistant State Geologist. Iowa Geological Survey, First and Second Annual Reports, State Geologist, pages 84-87, Des Moines, 1868.
- Surface geology of Raccoon River region. Iowa Geological Survey, First and Second Annual Reports, State Geologist, pages 173-190, Des Moines, 1868.
- Geology of middle region of western Iowa. Iowa Geological Survey, First and Second Annual Reports, State Geologist, pages 191-201, Des Moines, 1868.
- Middle Coal Measures of Iowa. Iowa Geological Survey, volume I, pages 264-284, Des Moines, 1870.
- Geology of middle region of western Iowa. Iowa Geological Survey, volume II, pages 1-13, Des Moines, 1870.
- [Geology of] Dallas County. Iowa Geological Survey, volume II, pages 13-46, Des Moines, 1870.
- [Geology of] Warren County. Iowa Geological Survey, volume II, pages 46-77, Des Moines, 1870.
- [Geology of] Lucas County. Iowa Geological Survey, volume II, pages 77-95, Des Moines, 1870.
- [Geology of] Guthrie County. Iowa Geological Survey, volume II, pages 95-130, Des Moines, 1870.
- [Geology of] Greene County. Iowa Geological Survey, volume II, pages 130-138, Des Moines, 1870.
- [Geology of] Carroll County. Iowa Geological Survey, volume II, pages 138-146, Des Moines, 1870.
- [Geology of] Calhoun County. Iowa Geological Survey, volume II, pages 146-150, Des Moines, 1870.
- [Geology of] Sac County. Iowa Geological Survey, volume II, pages 150-158, Des Moines, 1870.
- [Geology of] Ida County. Iowa Geological Survey, volume II, pages 158-164, Des Moines, 1870.
- [Geology of] Audubon County. Iowa Geological Survey, volume II, pages 164-171, Des Moines, 1870.
- [Geology of] Shelby County. Iowa Geological Survey, volume II, pages 171-174, Des Moines, 1870.
- [Geology of] Harrison County. Iowa Geological Survey, volume II, pages 175-182, Des Moines, 1870.
- [Geology of] Monona County. Iowa Geological Survey, volume II, pages 182-186, Des Moines, 1870.
- [Geology of] Woodbury County. Iowa Geological Survey, volume II, pages 186-200, Des Moines, 1870.
- Paleontological collections. Annual Report of the Committee on the Museum of Comparative Zoology for 1873, pages 19-21, Cambridge, 1874.
- Description of fossil vertebrates. Illinois Geological Survey, volume VII, pages 245-288, Springfield, 1875. With A. H. Worthen.

- Geology of northeastern New Mexico. *American Journal of Science* (3), volume XIII, page 219, New Haven, 1876. Abstract.
- Notes on geology of northeastern New Mexico. *Bulletin of the United States Geological and Geographical Survey of the Territories*, volume II, pages 279-308, Washington, 1876.
- Report of geological field-work of Teton Division. *United States Geological and Geographical Survey of the Territories*, Eleventh Annual Report, pages 321-508, Washington, 1877.
- Field-work of Teton Division. *American Journal of Science* (3), volume XV, page 58, New Haven, 1878. Abstract.
- Paleontological peculiarities of Blackfoot Mountains, Idaho. *American Naturalist*, volume XII, page 103, 1878.
- Description of fossil fishes. *Illinois Geological Survey*, volume VII, pages 53-264, Springfield, 1883. With A. H. Worthen.
- Report on geology of Wind River district. *United States Geological and Geographical Survey of the Territories*, Twelfth Annual Report, part i, pages 173-269, Washington, 1883.
- Notes on geology of southeastern Kansas. *Fifth Report of the Kansas Board of Agriculture*, part ii, pages 132-152, Topeka, 1887.
- Kansas. Macfarlane's *Geological Railway Guide*, second edition, pages 274-289, 1890.

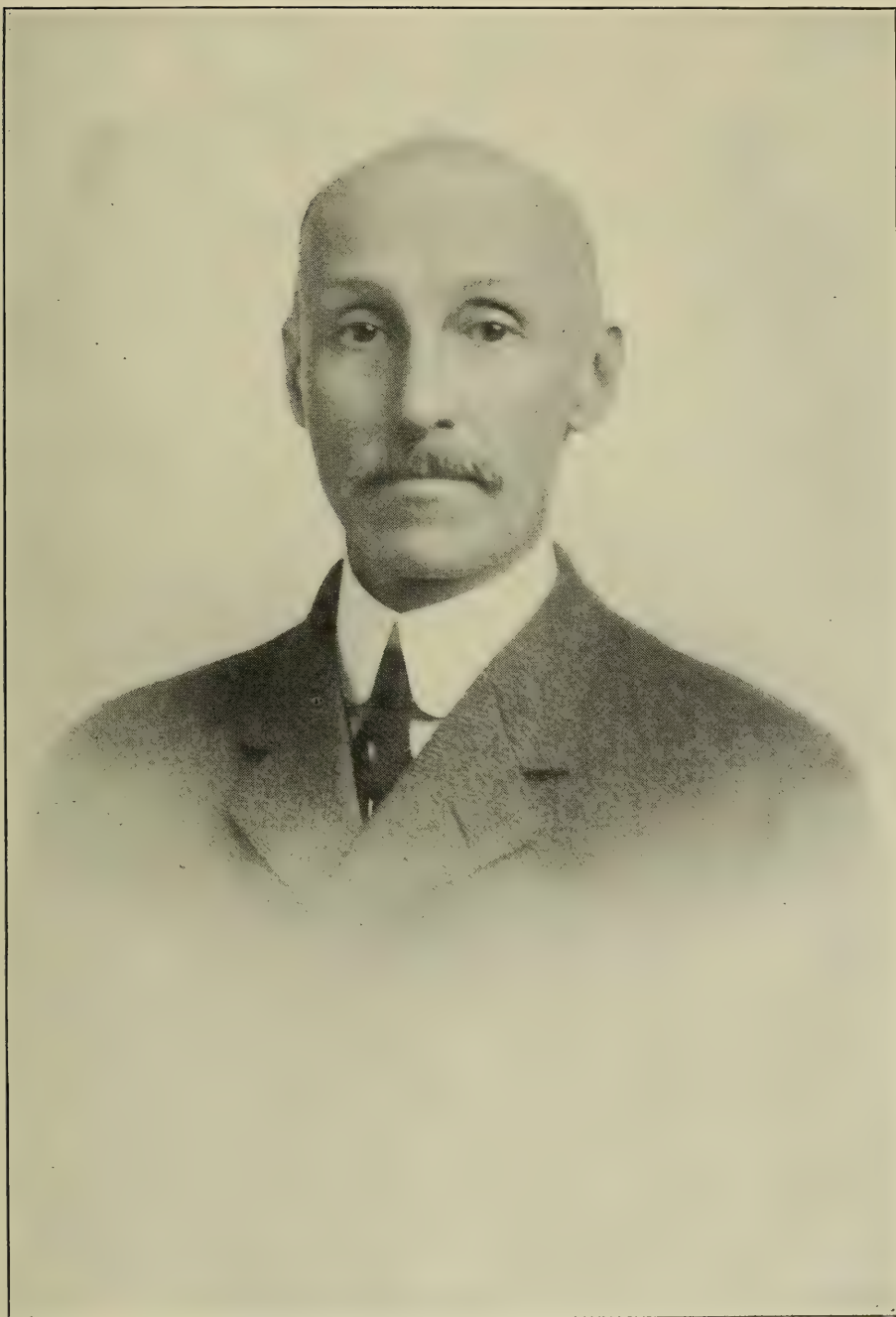
MEMORIAL OF HENRY PLATT CUSHING¹

BY JAMES F. KEMP

Henry Platt Cushing was born in Cleveland, Ohio, October 10, 1860. Two generations of his family had then been residents of the city and his father was at the time, and continued to be for many years thereafter, one of the leading and most respected physicians in the community. Father and son had grown up with the city and had felt a deep pride in its expanding size and influence, as well as a deep devotion to its welfare. Henry Cushing was the second of several sons, of whom two followed their father in the practice of medicine—one, Edward F., in Cleveland, and one, Harvey, the present Professor of Surgery at Harvard University. The earliest American ancestor, Peter Cushing, came from England to Hingham, Massachusetts, in 1638.

Henry Cushing was prepared for college in the Cleveland High School and entered Cornell University with the class of 1882, graduating with the degree of Ph. B. in due course. Returning for graduate study, especially in geology, he took the degree of M. S. at Cornell in 1884 and passed the next year studying at the School of Mines, Columbia University, under Prof. John S. Newberry. Dr. Newberry was an old-time

¹ Manuscript received by the Secretary of the Society January 17, 1922.



H. P. Tushnet.

citizen of Cleveland and had gone from the practice of medicine there to be naturalist and surgeon on western exploring expeditions in 1855. Later he was State Geologist of Ohio. During this year, 1884-85, the writer was also working under Professor Newberry, and began a close friendship with Harry Cushing which knew no change during his life. We two, with the late Frederick J. H. Merrill, made a trio of graduate students under one of the veterans of American geological science. At the close of the year, Henry Cushing was appointed to teach several branches in natural history at the State Normal School, Mankato, Minnesota, and remained there until 1891. He then passed a year of study in Munich, working under Groth and Weinschenk. Returning to America, he was called to be instructor in geology and chemistry at Western Reserve University, which had moved shortly before from Hudson, Ohio, to his native city of Cleveland. He held this position for two years. Promotion to an associate professorship of geology followed in 1893, and to the professorship in 1896. In this chair all the remaining twenty-five years of his life were passed. In 1909 Professor Cushing completed the requirements for Ph. D. at his *alma mater*, Cornell, and received the degree at commencement of that year.

While yet an undergraduate in college, Henry Cushing developed a deep and keen interest in geology. He worked with Professors S. G. Williams and H. S. Williams. The former had been in charge of the high school in Cleveland in earlier years and took a lively interest in the student from his old home city. For this formative and guiding interest Professor Cushing often expressed in after years his deep sense of indebtedness. His later relations with Professor Newberry and in time with Professor Weinschenk were also regarded as important influences in his career. In the publication of his early work he owed much to the support of Prof. James Hall, and in his later years to that of Dr. John M. Clarke, each of whom, though primarily interested in paleontology and stratigraphy, gave from his available resources relatively generous support to Professor Cushing's studies in the Precambrian.

Professor Cushing's first published work was a short paper on the Berea grit in northeastern Ohio, which was read before the Cleveland meeting of the American Association in the summer of 1888, the meeting at which the Committee of Organization of the Geological Society of America was appointed. Two years later he made a trip to the Muir glacier, Alaska, and from his observations prepared the three titles of 1891-93 which will be found in the appended bibliography. These papers foreshadow the extreme care and conscientious accuracy which characterize all his work.

In the closing years of the eighties and early years of the nineties the writer had become interested in the problems presented by the geology of the eastern Adirondacks, and when C. H. Smyth became established as professor of geology at Hamilton College, in 1891, we two, being friends of several years, formed an understanding that we would work in cooperation on the east and west sides of this little known Precambrian area. After a year or two we learned that our old friend, Professor Cushing, now established at Cleveland, was desirous of joining us in the work; so that we informally agreed to share the area and continue our studies in close cooperation, Professor Cushing taking the northern or northeastern portion. Prof. James Hall, State Geologist, did what he could for all three of us, but it is fair to state that an opportunity to work in the field with an avenue of publication was what appealed to each of us, and no one of the three allowed the matter of field expenses to stand in the way of gathering observations. In the early work the contour maps, which began to be available in the closing years of the last century, were lacking. County atlases, with their great inaccuracies, were the best maps which could be had. Almost inevitably the unit of the field-work was the town, as the western "township" is officially called in New York State, and the town or township maps were grouped by counties in the early reports. As a result, we find Professor Cushing's first report to be one on Clinton County, in the extreme northeast, and to contain a series of town or township maps.

While primarily engaged with the Precambrian, no one of us in areal mapping could escape being busied also with the early Paleozoic formations, and thus we see that Professor Cushing's next contribution relates to the faults in the Cambro-Ordovician strata in Chazy township. As time went by, his interest in the Cambrian and Ordovician sediments grew very strong, and their subdivision in the circumferential area around the Adirondack Precambrian became one of his main lines of research. The titles in his bibliography under the years 1908, 1909, 1910, 1911, and 1916, as well as important chapters in his New York State bulletins on several quadrangles, attest his activity in these lines. In his latest years the strain of field-work in the rough mountainous country proved severe. His studies were therefore carried on in the more open and flatter quadrangles along the Saint Lawrence and at Saratoga Springs, and finally were devoted to stratigraphic problems in the vicinity of Cleveland, extending from the Chagrin shale of the Upper Devonian to the Sharon conglomerate at the base of the Pennsylvanian. One of these relating to the Berea grit was the subject of his very first paper. His latest efforts were given to the preparation of the Cleveland folio. Despite his valuable contributions on Paleozoic stratigraphy, Professor

Cushing's chief work has related to the difficult and elusive problems of the Precambrian in northern New York, and by these he will be always best and most widely known. He was an observer of great accuracy and of keen insight, with an unusual gift for well grounded interpretations. His conclusions have rarely, if ever, been seriously modified by the subsequent study of other careful students.

His first contributions on Clinton County, 1894 and 1897, in addition to the detailed areal geology, established the last northeasterly appearance of the anorthosite and the great local abundance of the diabase dikes. Aside from some additional small exposures of gneiss, the county is made up of Cambrian and Ordovician strata. The dikes at Rand Hill were described in great detail in 1901.

In 1895 and 1896 Dr. James Hall was anxious to have the boundaries of the Potsdam sandstone along the northern border of the Adirondacks accurately mapped, and assigned Henry Cushing to the task. While tracing its limits, Professor Cushing was impressed with the relations of the trap dikes to these sediments. The subject of the dikes was one of lively interest among the three of us working in the Adirondacks, following the issue in 1893 of Bulletin 107 of the U. S. Geological Survey on the trap dikes of the Lake Champlain region. Professor Cushing became convinced that the Potsdam sandstone lay always over the diabase dikes, which were to be observed in the neighboring Precambrian, and that therefore these dikes were pre-Potsdam. This interesting observation is elaborated in the second title for 1896, which quite definitely established pre-Potsdam intrusives in addition to the already demonstrated post-Ordovician dikes of the Champlain Valley.

In the summer of 1898, while working along the cuts recently made near Loon Lake station for the new Mohawk and Malone division of the New York Central Railroad, Professor Cushing found slabs and blocks of Grenville limestone and associated strata caught up in an intrusive gneissoid rock of syenitic composition, and the first of the titles for 1899 resulted. This observation was of great importance. C. H. Smyth had, indeed, described intrusive syenites some time before from the west side of the mountains, and the writer had noted the mineralogy of these gneissoid augite syenitic gneisses at Ticonderoga and one or two other places, but the work near Loon Lake conclusively showed that, despite its gneissoid character, the syenite in the eastern mountains was intrusive and that it was later than the Grenville. There remained now the interesting time relations of the syenite series to the anorthosites. Proof positive of these relations was not found until the work on the Long Lake Quadrangle, whose publication came in 1907. Professor Cushing in this

Bulletin, page 481, figures an offsetting dike of syenite cutting massive anorthosite; so that we then became well aware that the syenites *followed* the anorthosites.

Meantime interest was directed to the outlier of old crystallines brought up by the great fault near Little Falls, on the main line of the New York Central Railroad. In 1902 Professor Cushing published a preliminary account of it and in 1905 a more elaborate description. To our great surprise, rocks long supposed to be gneissoid anorthosites, from superficial examination, proved to belong to the now well recognized syenite series.

In studying the Pleistocene history of the Hudson-Champlain Valley, Prof. J. B. Woodworth discovered in 1901 the extraordinary basaltic plug or other form of outbreak at Starks Knob, Northumberland, ten miles east of Saratoga Springs, and on the west bank of the Hudson River. Professor Cushing's aid was invoked for the petrographic study, and the paper cited under 1903 resulted. This extraordinary and isolated knob of glassy and brecciated volcanic rock is one of the strangest things in New York geology and has in later years been made a small State reservation. To its study Professor Cushing returned in connection with his work in the Saratoga Springs region and published a more detailed description in the Bulletin of the Geological Society in 1913. Its exact nature has not yet been fully determined.

In 1905 appeared also the "Geology of the northern Adirondack region"—a very valuable summary of results obtained up to that time and containing comparisons with the work of Kolderup in Norway on rocks extraordinarily like our anorthosites and syenites. Two years later the Bulletin on the Long Lake Quadrangle, already mentioned above, in order to bring the age of the syenites to complete statement, was issued and contained also some valuable observations on a mass of intrusive granite, the Morris granite, which cut both anorthosites and syenites and was therefore later than either. In the same year came the suggestive paper on the "Asymmetric differentiation in a batholith of Adirondack syenite," in which the outer borders of the great intrusive mass were shown to be higher in silica next the older granite gneisses and lower next the older anorthosite. Absorption and infusion of these wall rocks were believed to cause the contrasts.

In this same year came the paper on the "Physical oscillations during the Cambro-Silurian in northeastern New York." It indicates the growing interest (already cited above) which Professor Cushing felt in the interpretation and classification of the Cambrian and Lower Ordovician strata.

By close observation in the field, checked by the help of the paleontologists, Ruedemann and Ulrich, and by the interpretation of the strata in oscillations of the foundation rocks, a more detailed and correct classification was attained for the Cambrian and Ordovician beds around the Adirondack Precambrian.

In 1907 Professor Cushing was one of the three representatives of the United States (C. R. Van Hise and J. F. Kemp being the other two) who joined with the three Canadian geologists (F. D. Adams, A. E. Barlow, and A. P. Coleman) in spending a month in the Adirondacks and in eastern Ontario, in preparation for a report on the correlation and nomenclature of the Precambrian formations on both sides of the national boundary.

In the succeeding years Professor Cushing began his studies in the northwestern corner of the Adirondack area of ancient crystalline rocks in the region of the Thousand Islands. In association with C. H. Smyth, the Precambrian formations were mapped and interpreted, while R. Ruedemann aided in connection with the faunas of the Paleozoic and H. L. Fairchild was busied with the Pleistocene. The resulting bulletin of the State Museum dealt with five quadrangles and brought out many important details. One of the first results was described in the first title for 1910. In it Professor Cushing was able to show that a granite normally red bleached out to white where it lay next to invaded Grenville limestone, some peculiar effect having been exercised on the color by the limestone. A second result was the establishment of intrusive granites of at least two ages. The older, called the Laurentian in conformity with Lake Superior usage, is post-Grenville, but is foliated parallel with the Grenville structures. The Laurentian granite was followed by the Alexandria syenite, presumably a northeastern extension of the syenite series of the Adirondack Mountains. One minor exposure of gabbro was also found. Certainly later than both Laurentian granite and Alexandria syenite is the Picton granite, which has abundant inclusions of both these older intrusions and also of the Grenville. Finally the usual diabase dikes close the Precambrian, or at least precede the Potsdam sandstone. Professor Cushing drew some interesting comparisons with the ancient crystallines to the east and remarked the increasing metamorphism as one goes eastward. The chapters on the early Paleozoic strata are also of great importance, and interesting correlations are tabulated and discussed with reference to the Trenton Falls, Mohawk Valley, Saratoga, and Champlain Valley regions.

Professor Cushing, in association with Dr. Rudolph Ruedemann, next took up the mapping of the Saratoga Springs area, since agitation to

make this famous locality of mineral springs a State reservation was very active. Both Precambrian and early Paleozoic strata are involved, but the region is a difficult one because of masking of the hard-rock geology by the excessive deposits of Pleistocene sands and drift. An extremely careful and, for the conditions, accurate map and description resulted and many valuable details were recorded, both on the Precambrian and Cambro-Ordovician strata.

In areal work Professor Cushing next undertook the mapping of the three quadrangles—Brier Hill, Ogdensburg, and Red Mills—at and around the city of Ogdensburg, thus continuing the work done in the region of the Thousand Islands at a locality farther down the Saint Lawrence River. Bulletin 191 of the State Museum resulted in 1917. The greater part of the area is covered with the early Paleozoic strata, but especially interesting exposures of the Grenville are described. Granite and syenite give material for comparisons with the similar rocks at the Thousand Islands.

The last field-work done by Professor Cushing in the Adirondack Precambrian was in the Gouverneur Quadrangle, lying east of the Thousand Islands area and south of that near Ogdensburg. We have as yet only a preliminary sketch in the title for 1918. The quadrangle contains some of the best exposures of the Grenville in the State and many of the famous old localities of the tourmalines and other silicates which have gone to all the mineral collections of the world. The complete bulletin will be awaited with deep interest by all students of the Precambrian.

In these later years we note that the thoughts of Professor Cushing naturally turned to generalizations on his extended experience in northern New York. The age of the complex series of its igneous rocks led to the first title under 1915. In this paper he stoutly maintains the wide difference in age in the two granites of the Thousand Islands, reviewed above, and their relations with the other definitely established intrusives of the mountains.

The laboratory investigations of N. L. Bowen, of the Carnegie Geophysical Laboratory, on the anorthosites, followed by studies in the field and publication, in 1917-1918, on the broad features of their laccolithic or batholithic nature in the Adirondacks, raised a question in which Professor Cushing was deeply interested. In 1917 he discussed the subject and supported the view that our field knowledge was of so indeterminate a nature as to make very difficult the decision as to whether the anorthosites and syenites formed a huge laccolith or bathylith.

In these later years Professor Cushing turned again to the study of the Mississippian strata in northeastern Ohio, the subject on which his very

first published paper was based. The unconformity at the base of the Berea grit and its diastrophic significance was discussed before the Geological Society of America at the winter meeting in 1914, and published in volume 26 of the Bulletin. Before this date, as will be seen in the bibliography for 1912, the age of the Cleveland shale had been discussed.

Professor Cushing's work in the field in the last two or three years of his life was curtailed by weakness of the heart which made any protracted physical effort out of the question. He was, however, able to continue his teaching until the fatal attack of appendicitis suddenly developed and carried him away, April 14, 1921.

Henry Cushing was a man of exceedingly high ideals in his scientific work and in his relations with his fellows. Of a frank, open, and loyal character, he was a true and valued friend to those who were honored with his intimacy. He was a fine and sensitive spirit, as are almost all men with quick and sure intuitive grasp of scientific truths. His care and accuracy in the field were exceptional and were applied with unwearying patience. His published work has the unquestioning confidence of those who knew how conscientiously it was prepared.

In 1898 Professor Cushing was made Librarian of the Geological Society and its library was placed under his care in Cleveland, a very central point as regards the membership. Professor Cushing retired from this office in 1913 and was elected Vice-President in 1914.

He was one of the eighty-eight Original Fellows of the Society—that is, the Fellows who accepted the invitation of the Committee of Organization to join and become members without formal election. Thirty-four were surviving at the time of his loss; thirty now remain. Professor Cushing was very regular in attendance at the annual meetings, and the pages of the Bulletin contain nine contributions from his pen, besides his periodic reports on the accessions to the library. The American Philosophical Society extended to him the honor of election to its membership in 1916.

Professor Cushing married, June 3, 1886, Florence E., daughter of Prof. S. G. Williams, of Cornell University, who was one of the thirteen who met at Ithaca and organized the Geological Society of America in December, 1888. Mrs. Cushing, with one of their three children, is living in Cleveland, and to her and her daughter the deep sympathy of the Fellowship is extended.

The writer desires to express his indebtedness to J. E. Hyde, Professor Cushing's colleague and successor in the chair at Western Reserve University, for much valuable aid in preparing this memorial and its bibliography.

BIBLIOGRAPHY.

1888. Notes on the Berea grit in northeastern Ohio. *Proceedings of the American Association for the Advancement of Science*, volume 36, pages 213-215.
1891. Notes on the Muir Glacier region, Alaska, and its geology. *American Geologist*, volume 8, pages 207-230, plates 3 and 4.
1892. Notes on the geology of the vicinity of Muir glacier. *National Geographic Magazine*, volume 4, pages 56-62.
Zur Genauen Kenntnis der Phonolithe des Hegaus. (With E. Weinschenk.) *Tschermak's Mineralogischen und Petrographischen Mittheilungen*, new series, volume 13, pages 18-38.
1893. The movement of Muir glacier. *American Geologist*, volume 11, pages 276-278.
1894. Preliminary report on the geology of Clinton County, New York. *Forty-seventh Annual Report of the New York State Museum*, pages 669-683, map. *Thirteenth Annual Report of the State Geologist for the year 1893* [New York], pages 473-489, map.
1895. Faults of Chazy Township, Clinton County, New York. *Bulletin of the Geological Society of America*, volume 6, pages 285-296, plate 12.
1896. Notes on the areal geology of Glacier Bay, Alaska. *Transactions of the New York Academy of Sciences*, volume 15, pages 24-34, plate 1. Abstract, *American Geologist*, volume 17, pages 61-62.
 On the existence of pre-Cambrian and post-Ordovician trap dikes in the Adirondacks. *Transactions of the New York Academy of Sciences*, volume 15, pages 248-252. Abstract, *American Geologist*, volume 17, page 407.
1897. Notes on hypersthene andesite from Mount Edgecumbe, Alaska. *American Geologist*, volume 20, pages 156-159.
 Report on the geology of Clinton County [New York]. *Fifteenth Annual Report of the New York State Geologist*, volume 1, pages 21-22, 499-573, plates 1-3, 13 figures, 1897; *Forty-ninth Annual Report of the New York State Museum*, volume 2, 1895, pages 499-573, plates 1-3, 13 figures, 1898.
1898. Accessions to library [of Geological Society of America] from March, 1897, to March, 1898. *Bulletin of the Geological Society of America*, volume 9, pages 443-452.
 Syenite-porphry dikes in the northern Adirondacks. *Bulletin of the Geological Society of America*, volume 9, pages 239-256, plates 17, 1 figure. Abstracts, *American Geologist*, volume 22, page 382 (one-quarter page); *American Naturalist*, volume 32, pages 534-535 (one-half page); *Science*, new series, volume 7, pages 80-81 (one-half page).
1899. Augite-syenite gneiss near Loon Lake, New York. *Bulletin of the Geological Society of America*, volume 10, pages 177-192, plates 19-20.
 Report on the boundary between the Potsdam and pre-Cambrian rocks north of the Adirondacks. *Fiftieth Annual Report of the New York State Museum*, 1896, volume 2; *Sixteenth Annual Report of the State Geologist*, 1898, pages 1-27, 2 figures, map.

1899. Die Labradorfelse des Westlichen Norwegens 1. Das Labradorfelsgebiet bei Ekersund und Soggendal. Von Carl Fred Kolderup. (Abstract of the above by H. P. C.) *American Geologist*, volume 24, pages 126-130.
1900. Preliminary report on the geology of Franklin County [New York], part 3. Eighteenth Annual Report of the State Geologist [New York] for 1898, pages 73-128, plates 1-8.
- Accessions to library [of Geological Society of America] from March, 1898, to March, 1899. *Bulletin of the Geological Society of America*, volume 10, pages 515-526.
- Accessions to library [of Geological Society of America] from March, 1899, to June, 1900. *Bulletin of the Geological Society of America*, volume 11, pages 617-628.
1901. Origin and age of an Adirondack augite syenite. Abstract, *Bulletin of the Geological Society of America*, volume 12, page 464; *Science*, new series, volume 13, page 100.
- Geology of Rand Hill and vicinity, Clinton County [New York]. Fifty-third Annual Report of the New York State Museum, 1899, volume 1, pages r37-r82, map. Nineteenth Report of the State Geologist [New York], 1899, pages r37-r82, map.
- Accessions to library [of Geological Society of America] from June, 1900, to June, 1901. *Bulletin of the Geological Society of America*, volume 12, pages 503-512.
1902. Recent geologic work in Franklin and Saint Lawrence counties [New York]. Fifty-fourth Annual Report of the New York State Museum, 1900, volume 1, pages r23-r82, 6 plates, map. Twentieth Report of the State Geologist, 1900, pages r23-r82, 6 plates, map.
- Pre-Cambrian outlier at Little Falls, Herkimer County [New York]. Fifty-fourth Annual Report of the New York State Museum, 1900, volume 1, pages r83-r95. Twentieth Report of the State Geologist [New York], 1900, pages r83-r95.
- The derivation of the rock name "anorthosite." *American Geologist*, volume 29, pages 190-191.
1903. Petrography and age of the Northumberland rock [volcanic plug]. Fifty-fifth Annual Report of the New York State Museum, 1901, pages r24-r29. Twenty-first Report of the State Geologist [New York], 1901, pages r24-r29.
- Accessions to the library [of the Geological Society of America] from June, 1901, to June, 1902. *Bulletin of the Geological Society of America*, volume 13, pages 547-556.
1904. Memoir of Peter Neff. *Bulletin of the Geological Society of America*, volume 15, pages 541-544, plate.
- Accessions to the library [of Geological Society of America] from June, 1902, to June, 1903. *Bulletin of the Geological Society of America*, volume 14, pages 567-576.
- Accessions to the library [of Geological Society of America] from June, 1903, to July, 1904. *Bulletin of the Geological Society of America*, volume 15, pages 587-596.

1905. Geology of the vicinity of Little Falls, Herkimer County [New York]. New York State Museum, Bulletin 77, 95 pages, 15 plates, 14 figures, 2 maps and section sheet.
Geology of the northern Adirondack region. New York State Museum, Bulletin 95, pages 271-453, 18 plates, including 2 maps, 9 figures.
1906. Underpinning of the city [Cleveland, Ohio]. Report of Board of Expert Engineers on stability of court-house building site [Cuyahoga County, Ohio], by direction of Cuyahoga County Building Commission, pages 22-24.
Accessions to library [of Geological Society of America] from July, 1904, to July, 1905. Bulletin of the Geological Society of America, volume 16, pages 595-604.
1907. Geology of the Long Lake Quadrangle. New York State Museum, Bulletin 115, pages 451-531, 20 plates, 2 figures, map.
Accessions to library [of Geological Society of America] from July, 1905, to October, 1906. Bulletin of the Geological Society of America, volume 17, pages 733-742.
How faults should be named and classified. Economic Geology, volume 2, pages 433-435, 1 figure.
Asymmetric differentiation in a bathylith of Adirondack syenite. Bulletin of the Geological Society of America, volume 18, pages 477-492, map. Abstract, Science, new series, volume 25, page 774.
Physical oscillations during the Cambro-Silurian in northeastern New York. Abstract, Science, new series, volume 26, page 403.
Report of a special committee on the correlation of the pre-Cambrian rocks of the Adirondack Mountains, the "original Laurentian area" of Canada and eastern Ontario. (With F. D. Adams, A. E. Barlow, A. P. Coleman, J. F. Kemp, C. R. Van Hise.) Journal of Geology, volume 15, pages 191-217.
1908. Lower portion of the Paleozoic section in northwestern New York. Bulletin of the Geological Society of America, volume 19, pages 155-176, map, 1 figure. Abstract, Science, new series, volume 27, page 407.
Accessions to library [of Geological Society of America] from October, 1906, to October, 1907. Bulletin of the Geological Society of America, volume 18, pages 671-680.
1909. Accessions to library [of Geological Society of America] from November, 1907, to November, 1908. Bulletin of the Geological Society of America, volume 19, pages 579-588.
1910. Bleaching of granite at limestone contacts. Abstracts, Science, new series, volume 32, page 220; Bulletin of the Geological Society of America, volume 21, page 786.
Age and relations of the Little Falls dolomite (Calciferosus) of the Mohawk Valley. (With E. O. Ulrich.) New York State Museum, Bulletin 140, pages 97-140. Abstracts, Science, new series, volume 32, page 192; Bulletin of the Geological Society of America, volume 21, pages 780-781.
Geology of the Thousand Islands region, Alexandria Bay, Cape Vincent, Clayton, Grindstone, and Theresa quadrangles. (With H. L. Fairchild, R. Ruedemann, and C. H. Smyth, Jr.) New York State Mu-

- seum, Bulletin 145, 194 pages, 63 plates, 14 figures, 6 maps. Also issued as H. P. Cushing's thesis for the degree of Doctor of Philosophy, Cornell University.
1910. Accessions to library [of Geological Society of America] from November, 1908, to November, 1909. Bulletin of the Geological Society of America, volume 20, pages 711-720.
1911. Nomenclature of the lower Paleozoic rocks of New York. American Journal of Science, fourth series, volume 31, pages 135-145.
1912. The age of the Cleveland shale of Ohio. American Journal of Science, fourth series, volume 33, pages 581-584.
1913. Northumberland volcanic plug. Bulletin of the Geological Society of America, volume 24, pages 335-350, 2 plates, 4 figures.
1914. Geology of Saratoga Springs and vicinity. (With R. Ruedemann.) New York State Museum, Bulletin 169, 177 pages, 20 plates, 17 figures, 2 maps, sheet of sections.
1915. Age of the igneous rocks of the Adirondack region. American Journal of Science, fourth series, volume 39, pages 288-294.
Diastrophic importance of the unconformity at the base of the Berea grit in Ohio. Bulletin of the Geological Society of America, volume 26, pages 205-216, 1 plate, 2 figures; Abstract, page 96.
1917. Geology of the vicinity of Ogdensburg (Brier Hill, Ogdensburg, and Red Mills quadrangles). New York State Museum, Bulletin 191, 64 pages, 6 plates, 2 figures, map.
Structure of the anorthosite body in the Adirondacks. Journal of Geology, volume 25, pages 501-509, 512-514.
1918. The Gouverneur Quadrangle. New York State Museum, Bulletin 196, pages 24-29.

REPORT OF THE COMMITTEE OF THE GEOLOGICAL SOCIETY OF AMERICA
ON THE TEACHING OF GEOLOGY

The Committee on the Teaching of Geology was then called on for its report. This was presented by the chairman, in the form of a paper, given in full below, entitled

DEMONSTRATION MATERIAL IN GEOLOGY ¹

BY HERDMAN F. CLELAND

(Presented orally before the Society December 28, 1921)

CONTENTS

	Page
Introduction.....	56
Apparatus.....	57
General discussion.....	57
Suggested apparatus.....	58
Apparatus already constructed.....	61
Geological models.....	67
General discussion.....	67
Models already constructed.....	68
Suggested geological models.....	74
Relief maps.....	75
Source of supply.....	75
Suggested relief maps.....	76
Block diagrams.....	76
Lantern slides.....	76
Topographic maps.....	77
Moving pictures.....	78
Animated block diagrams or cartoons.....	78
Moving pictures of scenery.....	80
Restorations.....	81
Geological specimens.....	82
Recommendations.....	82
Discussion.....	84

INTRODUCTION

The Chairman of the Committee on Teaching of the Society sent out a questionnaire to Fellows of the Society and others to learn what demonstration material is in use in the colleges, universities, and museums of the United States and Canada and what, in the opinion of teachers of geology, survey men, and curators of museums, should be made or used. More than sixty replies were received, and it is to these that this report is largely devoted.

The attitudes of different correspondents toward demonstration material is interesting and suggestive: Survey men, on the whole, place the emphasis on field-work; the members of the geophysical laboratory and structural geologists state that apparatus of formative processes is much, possibly most, needed; a number of successful teachers, especially those

¹ Manuscript received by the Secretary of the Society March 11, 1922.

of the older school, think that demonstration material, in general, should be used infrequently; physiographers, as a rule, incline to the belief that, aside from maps and lantern slides, little is needed.

The importance of field-work as compared with other kinds of instruction was repeatedly pointed out. The opinion of an eminent field geologist on the relative value of lectures, demonstration material, and field-work is worthy of earnest consideration. He writes:

"It was not until Lawson came to the University of California and organized field excursions on Saturdays that I became really interested in the subject. Le Conte's lectures, admirable as they were, would never have made me a geologist. Therefore I believe that the committee might well concern itself primarily with field instruction in geology. Here, of course, some colleges are, by situation, far superior to others. The problem is to make the most of the surroundings and to arouse interest in the geological processes and results that are at hand."

APPARATUS

GENERAL DISCUSSION

By demonstration, or illustrative material, is meant apparatus, geological models, relief maps, topographic maps, lantern slides, and moving pictures of animated block diagrams.

The committee endeavored to learn what apparatus is in use in North America, but no especial effort was made to discover what is employed in Europe. It also urged geologists to indicate what apparatus, if any, should be constructed. In asking these questions the committee did not mean to imply, as the writers of some letters understood, that apparatus is as important as, or more important than, good teaching. For example, one man says:

"I do not believe geology is to be advanced *primarily* by apparatus of any kind, useful as apparatus is."

If by the use of apparatus it is possible to impart knowledge more effectively than in any other way, apparatus should be used, and for this reason attention was directed to the subject.

Arthur L. Day, of the Geophysical Laboratory, writes:

"Judging by the inquiries which frequently come to us, [geological apparatus] . . . is frequently in demand, and, if properly advertised, would find as ready and general a market as physical apparatus does among universities. What is needed is not plaster models of formations, but rather models representing the action of formative processes."

Prof. W. M. Davis, however, while appreciating the value of apparatus,

thinks that it imposes too great labor on the teacher, and consequently will not be largely used in the class-room.

SUGGESTED APPARATUS

The reply of Fred E. Wright,² of the Geophysical Laboratory, is especially suggestive. He says:

"Practically all the phenomena which the geologist has to consider involve spacial relations. Thinking in terms of space dimensions is not easy, and any models which aid the student to visualize and interpret three dimensional relations are welcome. It is for this reason, I take it, that the body of your letter is devoted to the consideration of models illustrating geological structural relations. Painted models of this sort do aid the purely geometric concepts, but they do not illustrate geological processes, and it is with the principles underlying these processes that the student should be most concerned. The geological structure is, in a measure, the end-product of a series of geological processes, and it is in the interpretation and history of these processes that we are most interested rather than in the formal description of structural relations as depicted in models." . . . "Experiments may be used to illustrate, for example, the mechanical behavior of rocks (elastic properties of materials, et cetera), the thermal behavior (thermal conductivity, diffusivity, et cetera), the physical-chemical behavior at different temperatures and pressures."

A. Under the heading of mechanical and elastic properties experiments may be set up to illustrate—

1. Formation of joint cracks.
 - (a) By mechanical means (Daubree's torsion experiment).
 - (b) By thermal means (rapid chilling of heated glass plates).
 - (c) By drying out (mud-cracks).
By volatilization (drying of rosin).
2. The elastic constants of rocks and materials.
 - (a) Compressibility (bulk modulus).
 - (b) Rigidity (shear).
 - (c) Tensile and crushing limits.
Phenomena of fracture.
 - (d) Plastic flow.
 - (e) Viscous flow.
 - (f) Behavior of bodies under hydrostatic pressure or tension.
 - (g) Behavior of bodies under load.
 - (h) Use of polarized light to show distribution of stresses in strained samples of glass, celluloid, or other transparent material.
 - (i) Elastic after-effect.
 - (j) Influence of temperature on these properties.

The importance of a thorough training in the principles of mechanics and the engineering attitude toward the elastic properties of materials, especially rocks, can not be over-emphasized.

² Letter received August 30, 1921.

B. Experiments on the physical-chemical behavior of chemical systems at different temperatures and pressures:

1. Crystallization phenomena.

- (a) Types of crystallization; effect of load.
- (b) Supersaturation.
- (c) Eutectics.
- (d) Sequence of crystallization.
- (e) Equilibria conditions.
- (f) Melting phenomena.
- (g) Inversion phenomena.
- (h) Gravitative settling and floating of different compounds on crystallization.
- (i) Exothermic and endothermic reactions.
- (j) Two component systems.
- (k) Zonal structure.

2. Liesegang experiments with colloids.

3. Settling of clays and suspensoid colloids.

4. Chemical corrosion.

5. Melting phenomena on ice blocks to illustrate iceberg formation.
Melting of ice under load.

C. Physical phenomena.

- (a) Geyser action.
- (b) Underground flow of water. Pore space.
- (c) Deposition of sediments in running water. (Experiments of Gilbert).

D. The principle of equilibrium.

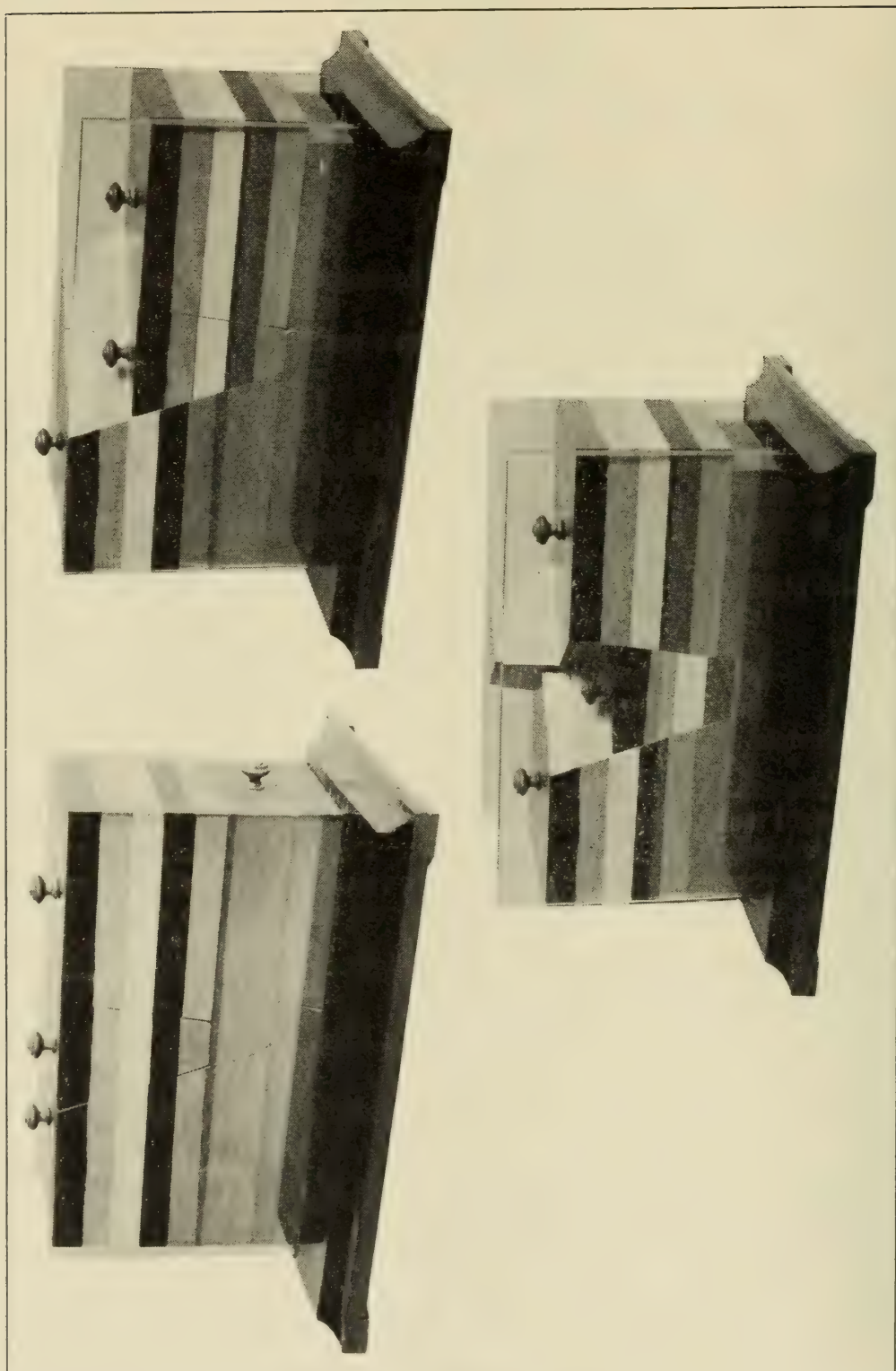
Most of the experiments listed above require simple, inexpensive apparatus only and might well be incorporated in a general course on geology. It should not be difficult to interest some manufacturer in the production of the required apparatus. A pamphlet describing these experiments might well be prepared by several geologists acquainted with the different phases of the work.

Most of the apparatus suggested by Wright is more suitable for advanced than for elementary students.

In addition to the apparatus suggested by Fred E. Wright, the following is desired by one or more geologists:

1. Apparatus to show the formation of volcanic cones of the explosive type.
2. Apparatus to show the method and origin of the Great Basin faults.
3. Apparatus for demonstrating folding.
4. Apparatus to show the operation of seismographs.
5. J. B. Woodworth suggests a piece of apparatus which he describes as follows:

"Draw an outline of the continent, with its political divisions and such other features as may be desired, on some form of flexible weighted stuff, so that the surface so prepared will rise and fall here and there above and below a



FIGURES 1, 2, AND 3.—Model to show the Effect of two Faults at right Angles to each Other

fixed imaginary plane. Let this map be placed over the necessary horizontal parallel rollers armed with projections or cams so arranged that when the rollers are set in motion in a given direction by a gear connecting them all, the parts of the map which were land in a given geological period will rise above the plane mentioned and parts which were water will sink below that plane. To complete the analogy, water may be introduced to the level of the plane assumed, and the design may be so arranged as to flood the submerged parts of the continent and to let the water flow away as elevation comes on. By a proper adjustment of the cams on the rollers, it seems possible to reproduce before the eye of the student the changes which are represented at their culmination on the so-called paleogeographic maps. The mechanism can be stopped, of course, at any stage, representing, say, the assumed distribution of land and sea in the Hamilton or in the Cincinnati stage. Corrections in the maps may be carried to the machine by correcting the length of the pegs or cams and changing their position as regards the time when they roll up and elevate or roll down and permit the sinking of the cloth map above them. A crank would suffice to turn the apparatus through the revolutions it was designed to execute."

APPARATUS ALREADY CONSTRUCTED

Some apparatus has been constructed and is already in general use and some little known apparatus should be more generally employed.

1. One of the best models to illustrate normal faulting is shown in figures 1, 2, and 3, but, as far as is known, there is but one copy in this country. The model is 18 inches long and 5 inches wide and consists of a block of wood inclosed between glass plates. The block of wood is cut by two diagonal faults at right angles to each other, and is so constructed that when the lower part of the block on the right is withdrawn a simple normal fault (figure 2) is produced, and when the lower part of the block on the left is removed a second fault (figure 3) forms. When the student has manipulated this model a few times he can readily visualize the appearance and understand the mechanics of "double" faulting which at first seemed to him very complex.

2. As students have difficulty in understanding slip, dip-slip, strike-slip, net-shift, and drag-dip, a model, such as that shown in figure 4, constructed after the diagram in the report of the Committee on the Nomenclature of Faults,³ has been found very useful. A convenient size is 6 x 12 x 3 inches. In making this model it is better to use one piece of wood; otherwise the model is liable to break at the fault-line.

3. Another very simple piece of apparatus (figures 5, 6, 7) illustrates the effects of both normal and thrust-faults on inclined beds. By turning back the hinged top of the back block, the effect of erosion on a region so

³ H. F. Reed, W. M. Davis, A. C. Lawson, F. L. Ransome: Report of the Committee on the Nomenclature of Faults. Bull. Geol. Soc. Am., vol. 24, 1913, p. 171.

faulted is seen. The model is also useful in demonstrating horizontal faulting, such as that which produced the San Franciscan earthquake, and can also be used to show hinge faults.

4. A piece of apparatus designed by Woodworth and Foye to show the principle on which the seismograph works and to demonstrate earth tilts was at one time on sale, but, as far as known, can not now be purchased. As students in elementary geology have difficulty in understanding, without a visual demonstration, how earthquake shocks are recorded on instruments, something of this sort should be made available.

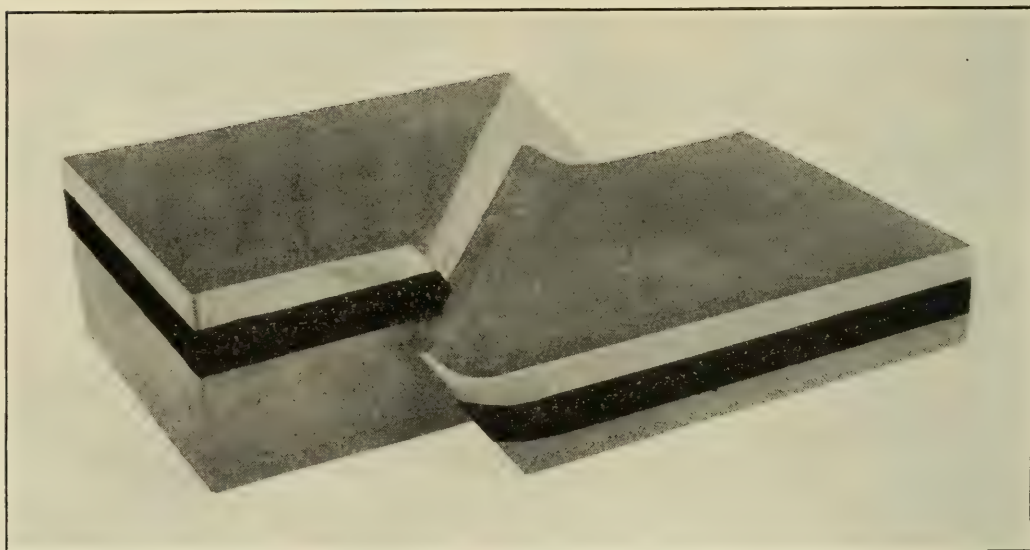


FIGURE 4.—Model which shows *Slip, Dip-slip, Strike-slip, Net-shift, and Drag-dip*

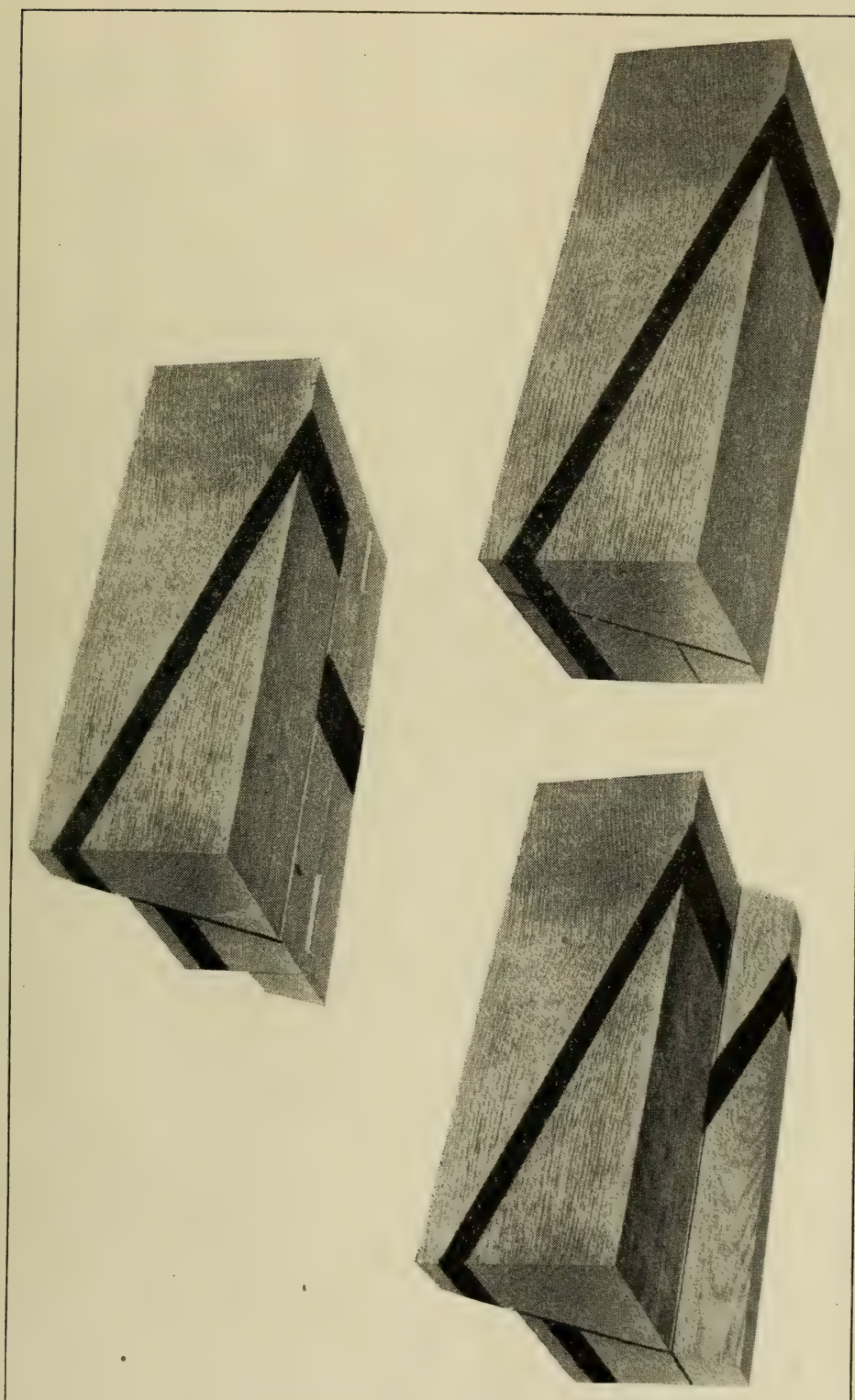
5. Jaggar's⁴ geyser experiment is one which has been found both interesting and useful. Snow's apparatus, as illustrated and described by Hobbs,⁵ is simpler and possibly better on that account and has been used for ten or more years.

6. Leith and Mead's netting model, designed to show non-rotational and rotational strains and shear, is simple and inexpensive and useful in advanced courses.

7. A piece of apparatus to show the path of a bundle of light rays reflected from a mirror and passing through a lower nicol prism, mineral section, and upper nicol in crossed position has been designed by Prof. F. Bascom and has proved very serviceable in petrography. No dealer has this for sale.

⁴ T. A. Jaggar: *Journal of Science*, 4th series, vol. 5, 1898, pp. 323-333. Snow's apparatus is illustrated in Hobbs' "Earth features," p. 193.

⁵ Leith: *Structural Geology*, pp. 18-21.



FIGURES 5, 6, AND 7.—Model to show the topographic Effect of a Dip-fault, before and after Erosion

8. R. H. Johnson offers a suggestion for the construction of structural models which deserves careful consideration. He says:

"Valuable models can be made from sheet lead mounted in a frame. This lead can readily be bent to illustrate structure and it can be painted later to bring out the geologic lines."

He made a structural map of the entire United States in this way. He states that such models can not well be made by a dealer, but that each teacher can, with patience and skill, construct his own models.

9. The Director of the United States Geological Survey writes that—

"A great deal of apparatus has been designed and used by members of the Geological Survey for studying various geologic phenomena, and some of it could doubtless be adapted for the use of schools. Among apparatus of this sort may be mentioned the compression machine used by Bailey Willis in his experiments on Appalachian structures; apparatus devised by Wentworth for the study of certain problems connected with sedimentary rocks; apparatus devised and used by Gilbert in his studies of debris transportation; Van Osstrand's apparatus for the study of the diffusion of solids; Melcher's apparatus for the study of the porosity and diffusion of oil and water through rocks, etc. None of this apparatus is for sale and much of it is too complex for general school use, but modifications might be made, so that the result would be simple, rather inexpensive, and adaptable for teaching."

Each teacher must decide for himself whether or not any of this apparatus can be used advantageously, but it seems probable that it will be found more useful in research courses than in elementary courses in geology.

10. Director H. Foster Bain,⁶ of the Bureau of Mines, states that—

"The Mills' experimental apparatus for studying the migration, accumulation, and recovery of petroleum and natural gas would be useful for the elementary class-room and laboratory and for investigational work by advanced students, as it would give the student the clearest possible understanding of the relations that structure, bedding, textures of sand, and other underground conditions bear to the migration, accumulation, and recovery of oil and gas. It might also be used for a model, or permanent exhibit."

Persons wishing to construct such apparatus should write to Mr. Mills. A model such as this would be of real value in elementary teaching.

11. Prof. W. M. Davis years ago constructed a working model illustrating his view of the faulting of the Triassic rocks of the Connecticut Valley, which, if so modified as to be less cumbersome, would be helpful in teaching faulting in general geology. In its present form it will probably not have a wider use than in the past. It is hoped that some in-

⁶ *Economic Geology*, vol. 15, p. 398; vol. 16, p. 124.

genious geologist will reconstruct the model, so that it will be more serviceable and attractive.

12. A piece of apparatus designed by W. H. Hobbs⁷ to teach students to interpret geologic maps by reproducing field conditions on a small scale, which has been successfully used at the University of Michigan for a number of years, is described in his "Earth Features." Similar apparatus has been employed in the University of Illinois and probably elsewhere.

13. H. G. Turner,⁸ of Lehigh University, has made a useful and inexpensive piece of simple apparatus for teaching dip and strike.

14. Stephen Taber,⁹ of South Carolina, has constructed apparatus for illustrating (1) the growth of crystals under pressure, (2) the growth of fibrous veins, and (3) expansive pressure due to hydration.

The apparatus described above will doubtless be of use for advanced students in economic geology, but not for elementary classes.

15. The sedimentary erosion apparatus used at the University of Wisconsin is shown in figure 8. The following description of the apparatus is by W. H. Twenhofel:

"The apparatus consists of two galvanized iron tanks and a glass tank. The larger galvanized iron tank is shown in the right background. It is open on one end, and from this end a trough of varying width connects with the smaller galvanized tank, the latter being shown in the left background. The glass tank is shown in the right foreground, and it is connected with the main trough by one considerably smaller. This trough is so arranged that it may be closed as desired. The glass tank has a galvanized iron bottom and one end is constructed of the same material. The two sides and the end into which water flows are made of glass, the end being inclined.

"Erosion in the large tank is brought about by means of a spray, which may be directed downwards, as shown in the photograph, so as to produce the effects of rapid erosion; or directed upward, so as to produce the effect of a gentle rain.

"The larger tank is mounted on a tilting-top table, which permits any corner or any side to be raised or lowered at will, giving the effect of a tilting or warping land. The slope of the trough is also adjustable. The material in the tank may be varied to meet the requirements.

"The smaller galvanized iron tank has three drains on the far end—one at the bottom, one about 6 inches from the bottom, and one a foot from the bottom. This permits adjustment of the water to any level, so that the effects of

⁷ W. H. Hobbs: Apparatus for instruction in geography and structural geology: Interpretation of geological maps. *School Science and Mathematics*, vol. 9, 1909, pp. 644-653; also, *Earth Features*, p. 64, figures 47 and 48.

⁸ H. G. Turner: Laboratory determinations of dip and strike. *Science*, vol. 1v, 1921, no. 1411, pp. 53-54.

⁹ Stephen Taber: *American Journal of Science*, June, 1916, vol. xli, pp. 532-536, figures 1, 2, and 3. *Am. Inst. Mining Engineers Bulletin*, no. 119, pp. 1973-1998.

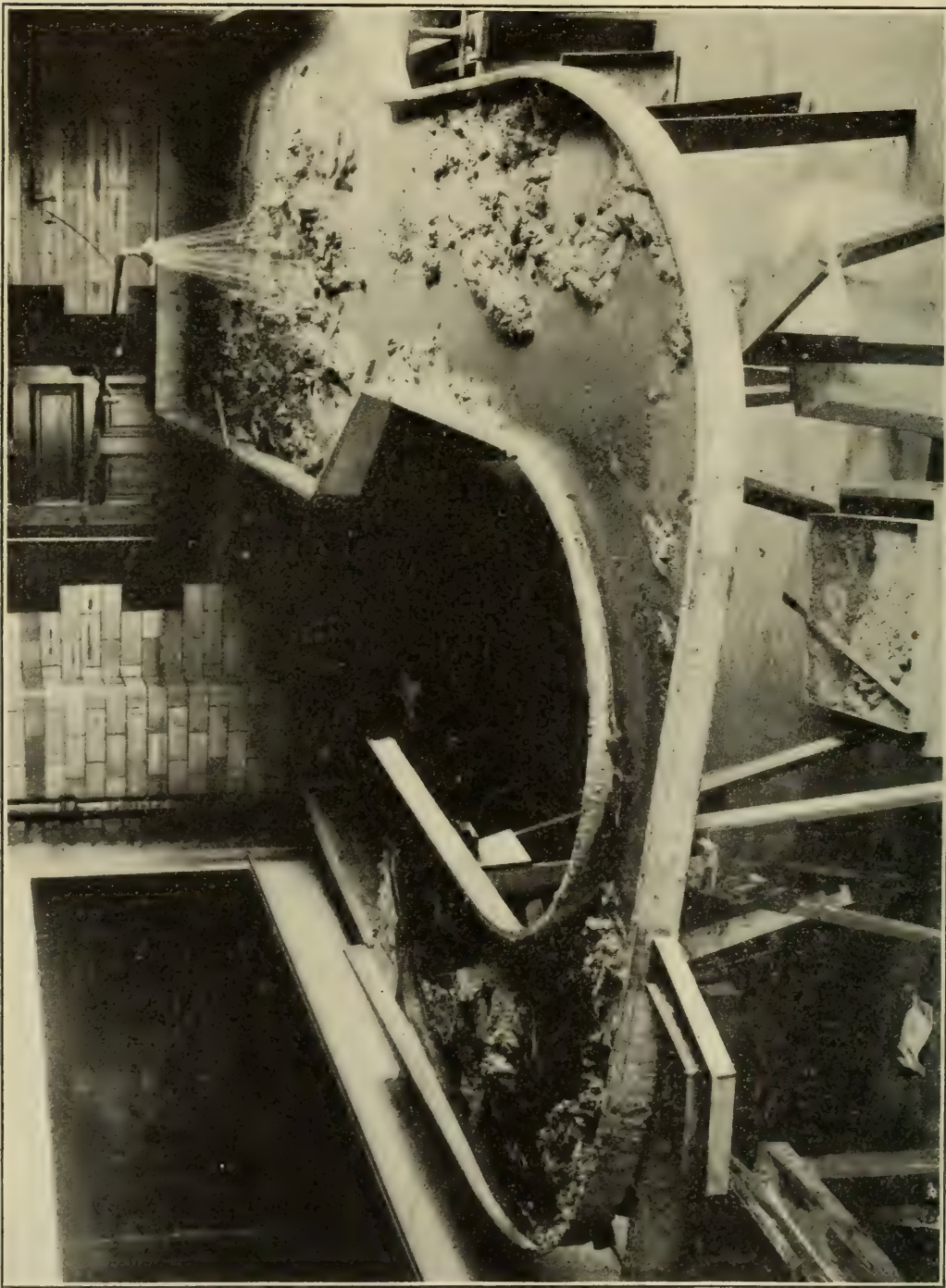


FIGURE 8.—Sedimentary Erosion Apparatus in use at the University of Wisconsin

submergence and emergence may be produced. In this tank deltas, wave-cut and wave-built terraces, unconformities, mud-cracks, bubble impressions, and other features are readily developed.

"The glass tank has four drains situated at the bottom and at 2, 8, and 12 inches from the bottom. The glass sides and one end permit observation of bedding and lamination and other features as they are being developed. In this tank may also be observed the contemporaneous deformation of sediments while the deformation is taking place. A long, narrow glass tank is now in process of construction in order to further study the contemporaneous deformation of sediments.

"In the trough the building of alluvial fans, the development of meanders, the process of stream erosion and deposition are readily demonstrated. A fan is shown in the trough in the right foreground."

GEOLOGICAL MODELS

GENERAL DISCUSSION

Many teachers of geology will probably be inclined to agree with one successful teacher who states as his belief that "we are more in need of good combined relief and structure models than any other material in our teaching." There must, however, be at least one qualification: the models must not be large. A model so large that it can not easily be handled is soon discarded as a part of lecture equipment and is left to accumulate dust. One reason that the models of Alpine structures sold by Kranz, of Bonn, are so widely and effectively used is that they are of convenient size. It is doubtful if models more than 3 feet long and 6 inches wide are suitable for the lecture table, and shorter ones are even more desirable. It is probable that most teachers of geology have bought or have made one or more geological-geographical models with the firm belief that such reliefs would prove most helpful in teaching, only to find that, because of the unwieldy character of the models, they could not be shown to advantage in the lecture-room. In the geological museum of one of our best universities there are on exhibition a number of fine geological-geographical models, some of which were made at great expense. Nevertheless, but few of the students of elementary geology of that university have seen them and still fewer have had them explained to them. This is not an isolated example, but will apply to the geological relief maps of most college and university museums. There is a real need for models of North American structures. It is surprising that so few structural models of this continent, suitable for class-room use, have been made, notwithstanding the fact that models of parts of this continent are much needed and illustrate common types of mountain structures much better than the models of the Alps.

MODELS ALREADY CONSTRUCTED

Some excellent geological models have been constructed, of which the following should be mentioned:

1. G. H. Hudson, of Plattsburg, New York, has made a model of the complex normal faulting of Valcour Island, New York (figure 9). This is an admirable model and brings out the complex structures which may result from normal faulting, and also the danger, under such conditions, of calculating the amount of section lost in any hiatus. If made somewhat larger and with the beds indicated by strongly contrasted colors, it would be a useful addition to our geological equipment.

2. No models better than the so-called Sopwith models, devised about 1841, to demonstrate the effects of normal faulting on coal beds and copper and tin veins, have yet been made, and these should be universally

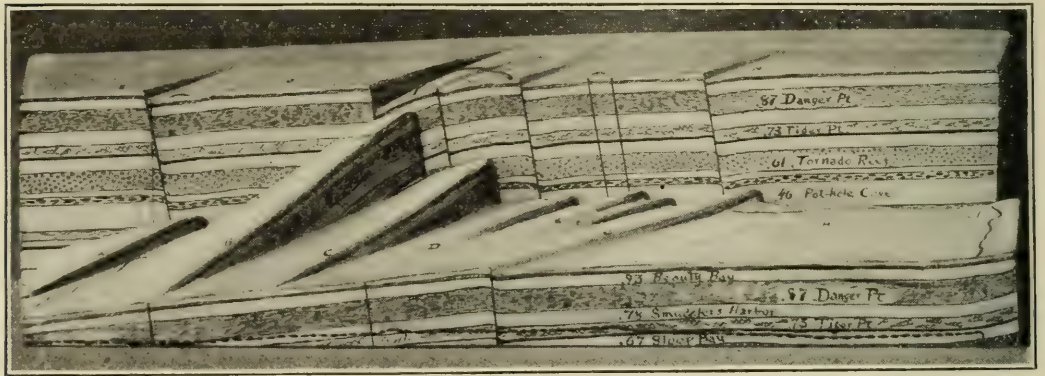


FIGURE 9.—Model of a Part of Valcour Island, Lake Champlain, New York

used. The models of faults and folds, sold by Krantz, are more easily seen on the lecture table than these, but are otherwise greatly inferior.

3. A number of painted boxes which both illustrate different kinds of folds and different kinds of faults have been made at the University of Chicago, but experience has shown that only one, which shows a pitching fold, is especially useful.

4. There are a number of geological relief maps in the Field Museum of Chicago, which, if slightly modified, of suitable size and with strongly contrasting colors, would, with little doubt, be a welcome addition to the teaching equipment in elementary geology and could also be used in advance courses.

a. One model of a small gold mine (figure 10) was made and primarily intended to illustrate methods of mining, but some features of vein structure are also reproduced. The model is about 4 feet long, 3 feet high, and 10 inches thick, the dimensions being governed by the space available for its exhibition. The scale is 10 inches to the foot. It represents a

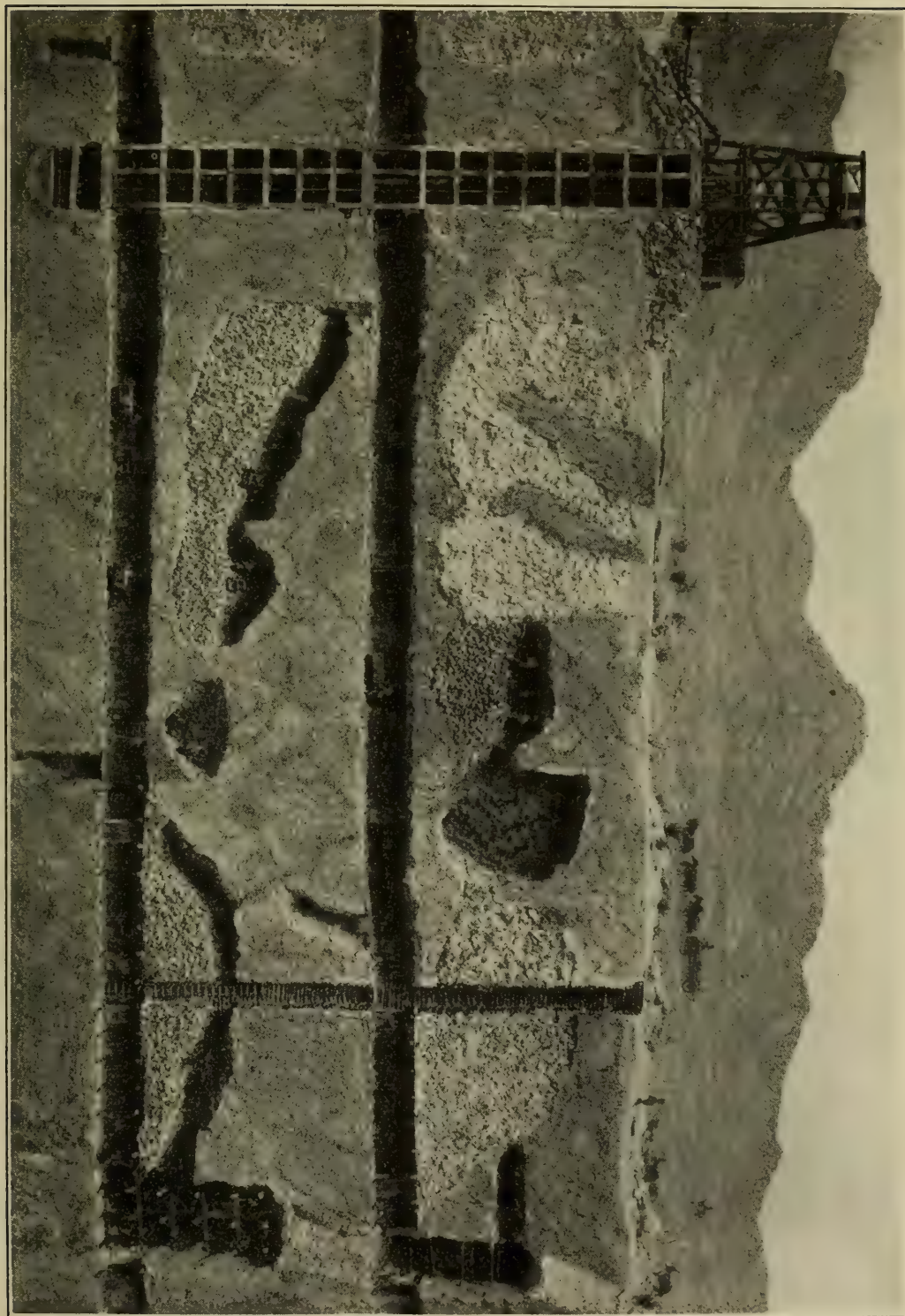


FIGURE 10.—*Model of a Gold Mine, Field Museum of Natural History*

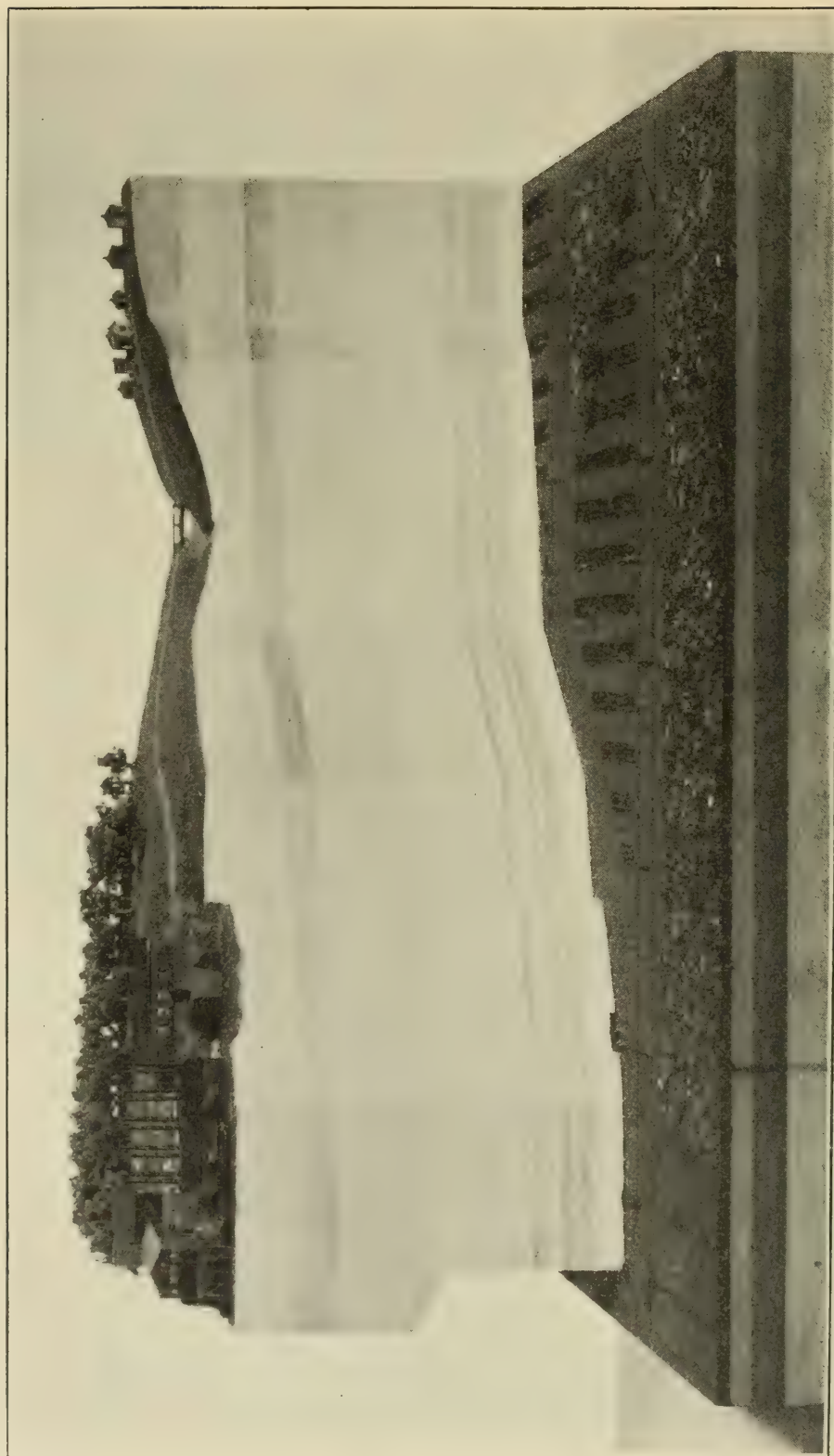


FIGURE 11.—*Model of a Coal Mine, Field Museum of Natural History*

longitudinal section of a vertical vein and is condensed from the workings of an actual mine, the Camp Bird, in Colorado. The condensation was accomplished by omitting all but one of any feature that is repeated in the actual mine. The important part of the model is the section which forms its face. Here the vein formation and several types of mine openings are shown. The sulphides of the ore are simulated by bronze paint for luster, toned down to the proper colors and luster by transparent washes of oil color.

b. Another model in the Field Museum is that of a coal mine (figure 11) which illustrates the mining as well as the geological occurrence of coal. This model is small, being about two feet square by one foot in height, and the scale is small—100 feet to the inch. It shows the surface

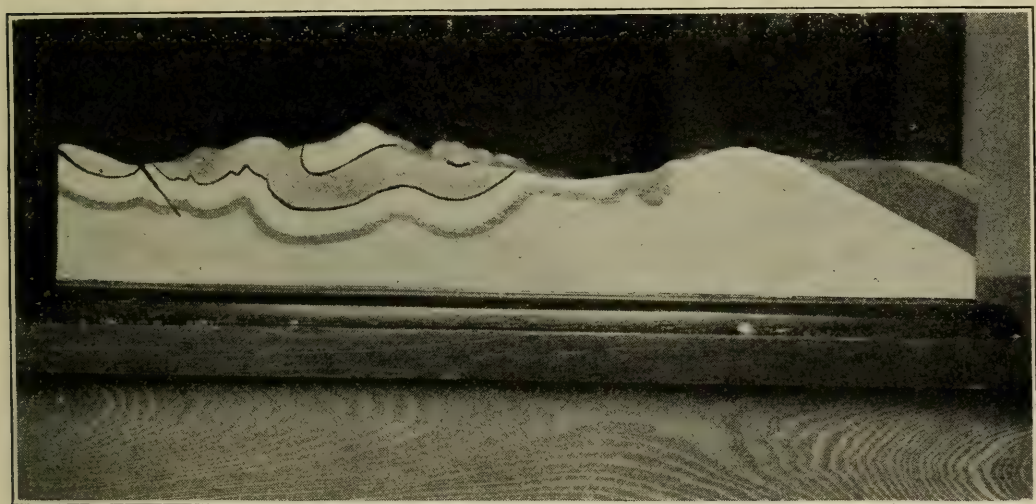


FIGURE 12.—*Model of the Mount Greylock (Massachusetts) Synclinorium*

of a coal mining region in Virginia, with colliery buildings in the rear. At the location of the main shaft the ground is cut away to the level of the roof of the coal bed and a geological section is reproduced on the vertical surface. The front half of the model is at the level of the coal seam and shows the coal and the workings with the roof removed.

c. A third model shows the relations of the topography of surface to that of the underlying rock in a glaciated region. The surface shows a rolling country, with fields and farm buildings. The front of the model is in the form of a section showing horizontally bedded limestone of the character of that underlying Chicago.

5. In the American Museum of Natural History, New York City, are a number of excellent geological models, among which is one of the Connecticut Valley and one of the Copper Queen Mine, Arizona. They are, however, too large for use in the class-room.

6. Large geological models of the Black Hills have been constructed by the South Dakota School of Mines, but are so large and expensive as to be impracticable for class-room purposes.

7. A geological model (figure 12) of the Greylock (Massachusetts) synclinorium has proved of considerable value in teaching.

8. D. B. Dowling, of the Canadian Geological Survey, has made a number of excellent geological-geographical models of the western plains and Rocky Mountains of Canada. They are rather large for lecture demonstration, but parts of several of them, if made of suitable size, would be of great value in teaching.

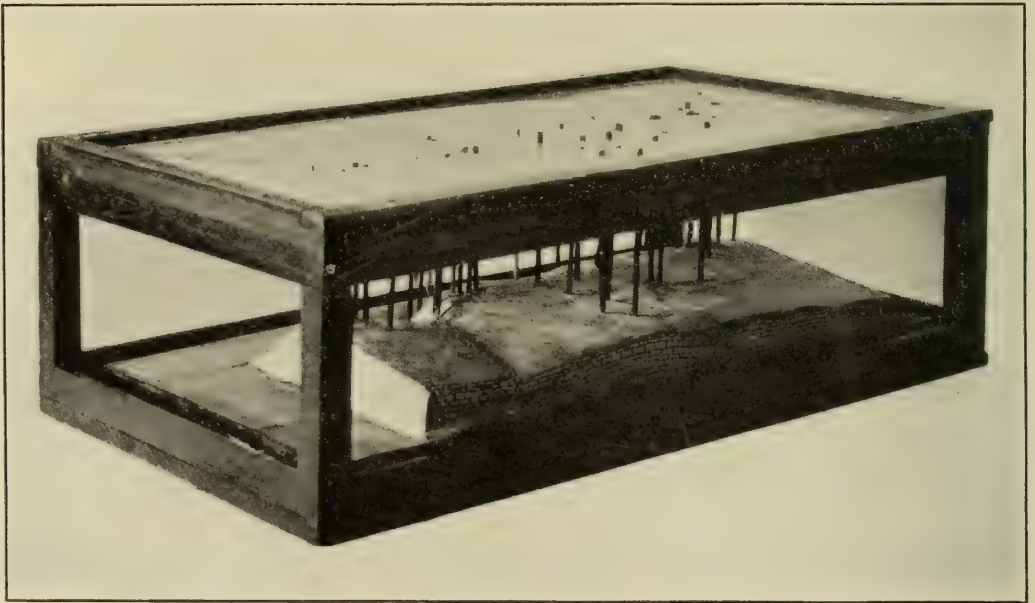


FIGURE 13.—*Model of a Mexican Oil Field*

This model shows the top surface of the oil-bearing formation and the salt-water contacts at different periods in the pool's history. The celluloid top represents the surface of the region. Made by L. G. Huntley.

9. F. D. Adams some years ago constructed a model showing the Montreal Hills, which illustrates dikes and other igneous phenomena. This model is one which, in some such form as that recommended above, would be of value in teaching.

10. The Shaler-Davis models, sold by Ward's Natural Science Establishment, are so well known that they need no description.

11. *a.* A model (figures 13 and 14) showing the structural features of a Mexican oil field (Tepetate-Chinampa), recently made by L. G. Huntley for use in court, is unusually well suited for demonstration purposes. The model consists of a subsurface section showing the folding in the Tamasopa limestone, on the top surface of which is drawn the oil-water

contact lines at different periods in the pool's history. The surface of the region is represented by a sheet of transparent celluloid, on which is drawn the map of the region; wooden pegs represent the wells drilled.

It is hoped that arrangements can be made by which this model can be offered for sale.

b. The model of the Hewitt field constructed by the Bureau of Mines, and described in Bulletin 195 of the Bureau, could probably be duplicated for about \$50. At least one such model could be used to advantage in elementary classes.

c. A peg model of a salt dome on the coast is being constructed by the

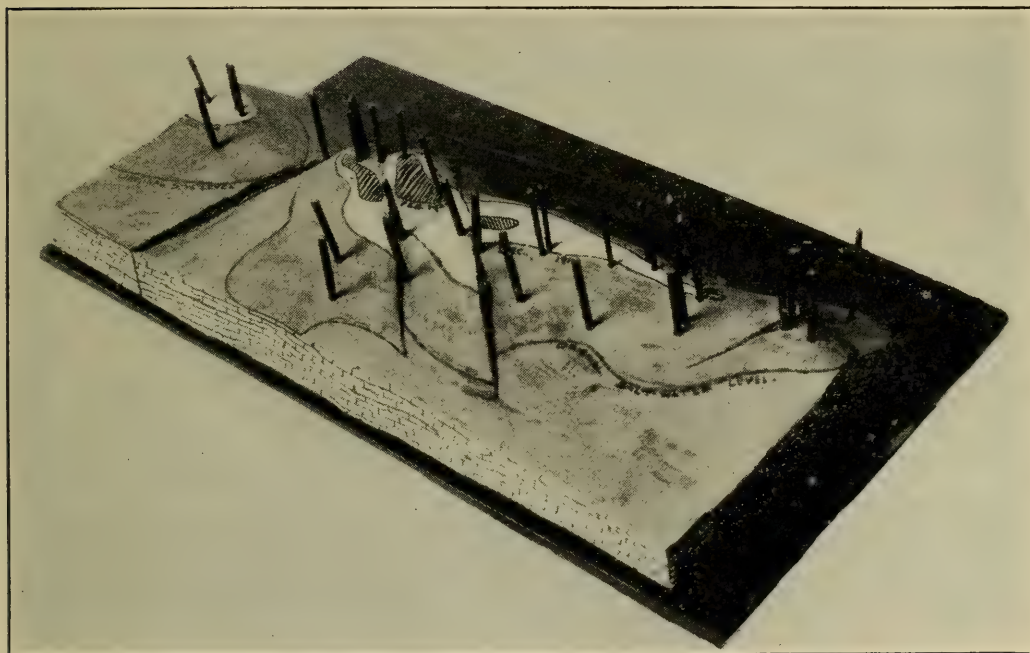


FIGURE 14.—Another View of the Model shown in Figure 13, top removed

Texas Geological Society, but whether it can be sold when completed is not yet known. This would probably be of value for advanced classes.

12. Prof. J. Austin Bancroft calls attention to a type of model, a modification of the "glass-plate" model, which he devised while working out the underground geology of a large mine. He secured large sheets of thick, transparent celluloid and used diluted India ink of different colors in outlining the geology of the various mine levels on these sheets. He had a wooden frame constructed whereon he could mount these geologically colored celluloid sheets in a manner similar to the ordinary glass model of a mine. Then he had made some dowel sticks, $1/16$ th and $1/8$ th of an inch in diameter, colored to show the geological formation passed through by each diamond-drill hole, and in order to give rigidity

to the model left each of the dowel sticks long enough so that it could be pushed into proper position and into a gimlet-hole in the wooden base on which the model was constructed. The same color was made use of for the same geological formation or the same phase of the formation, both on the celluloid sheets and the dowel stick. Moreover, the vertical scale of the model was kept the same as the horizontal scale. When complete the model enabled one to see things exactly as they existed in the mine and to project downward the geological relations in such a manner as to prophesy definitely what might be encountered at depth. Models of this kind are expensive and entail much work, but if money were available a few should be made for use in courses in economic geology.



FIGURE 15.—*Example of a relatively inexpensive Exhibition useful in Teaching*

In this connection attention should be called to the desirability of arranging inexpensive but helpful study exhibitions, such as that shown in figure 15.

SUGGESTED GEOLOGICAL MODELS

Among others, the following geological models could be used to advantage in the class-room and laboratory if made of suitable size:

1. Two or more models of east-west Appalachian sections, with a detachable cap showing the parts removed by erosion. One, for example, from Harrisburg to Tyrone, and one or more across the southern Appalachians, where thrust faulting is strikingly shown. In other words, sections of mountains of what R. T. Chamberlain calls the "thin-shelled" type.

2. Several models of mountains of the "thick-shelled" type, such as the Rocky Mountains.

3. A model showing a section across the Sierra Nevada.

4. One of the Coast Ranges.

5. One of the Ozarks.

6. Two of the Black Hills; one a generalized section of the whole mountain mass and the other a detailed section of the central crystalline mass.

7. A model showing a section across the basin of Mexico City.

8. A model showing a section across the Rocky Mountains at Banff.

9. One of the eastern townships of Quebec, showing a section across the Monteregian Hills (splendid residual mountain cores).

10. A model of the Bannock overthrust.

11. An accurate model of the Karst regions of Florida and Dalmatia, showing especially underground structures.

12. An east-and-west section across the Hudson Valley, near New York City, and including the Palisades.

13. A model in which piedmont foldings and intrusions are well shown.

14. A model of the Cincinnati anticline.

15. A model which shows the geological section of a narrow strip of country across the Mohawk River from the Adirondacks to the Catskills.

16. Models, with sections, of the Great Plains of the United States.

17. A model of a coastal plain to show cuestas and the varying thickness of the coastal plain formations, such as are well illustrated in parts of Alabama, Mississippi, and Texas.

18. Models showing the structure of the Green and White Mountains, if any one has the knowledge or courage to attempt them.

19. A model of the complex structure of the Lake Superior region.

20. Fine geological models of our national parks should be on exhibition in all of the parks, and class-room models should be made available. It is a fortunate circumstance that our national parks, though chosen for the most part without regard to their geological structure, furnish, nevertheless, excellent examples of diverse geologic and physiographic types.

Other models will doubtless suggest themselves.

RELIEF MAPS

SOURCE OF SUPPLY

So many relief maps have already been constructed by museums, geological surveys, universities, and colleges that space will not permit of

their enumeration. Robertson Brothers of Washington, Ward's Natural Science Establishment of Rochester, The Lorenz Model Company of Madison, and Krantz of Bonn are the principal dealers.

SUGGESTED RELIEF MAPS

The answers to the questionnaire indicate, however, that a number of relief maps are desired. Of these only a few will be indicated:

1. It might be well to construct three relief maps, each about one foot square, to show sink-holes, pot-holes, and kettle-holes.

2. A set of three relief maps to show how a mountain range may be cut back by "cirque action." An ideal landscape, based on Cloud Peak and Phillipsburg, Montana, topographic sheets, might be used.

3. Another set of relief maps might be made to show stream capture of the normal type, stream piracy by subterranean drainage, and capture by planation.

4. One letter urges the construction of paleogeographic relief maps.

Prof. W. M. Davis gives the following warning:

"A really educational series can not be limited to actual areas. . . . All good teaching that I know of takes artificial examples or artificially limited and selected and simplified examples to begin with. . . . Furthermore, the models should be in series to illustrate relationships. Finally, they should be associated with models of actual places; but of the two, the ideal are much more instructive."

BLOCK DIAGRAMS

In this connection reference should be made to the value of block diagrams. Although models give a better mental picture of topography and geological structure than anything else except nature itself, and in some models even better than nature, block diagrams are invaluable. Nothing has made the study of geology and physiography more real than the remarkable block diagrams of Prof. W. M. Davis and those of his students and followers. The advantage of diagrams of this kind lies in the fact that they can be taken to his room by a student and studied at any time.

LANTERN SLIDES

All the correspondents but one appear to believe firmly in the use of lantern slides in teaching geology and physiography, but no entirely satisfactory plan for enabling teachers to know what slides are in existence and how they can be obtained has been suggested.

The most practical suggestion is that this matter should be left in the hands of some permanent organization.

(1) A number of correspondents suggested that the Geological Society of America appoint a committee to establish an office to which titles and negatives could be sent, but the changing personnel of a Geological Society committee makes such a solution impractical; (2) others that the proposed Federal Department of Education should establish a clearing-house for lantern slides; (3) others that the Geologic Survey be urged to take hold of the matter; and still others that the National Research Council take this up as a part of its work.

The Federal Survey has 80,000 photographs and a large staff of trained geologists and geographers and could, without doubt, do this work better than any other organization. Director George Otis Smith writes that the Survey will be glad to cooperate in making more available the Survey photographs, provided that it can be done without entailing considerable additional expense.

This is a matter which requires careful and immediate attention, and it is hoped that one of the above solutions or some better one may be found.

It is, perhaps, evident to all teachers of geology and physiography that many of the lantern slides shown in class, especially if they are from negatives taken by the teacher, are not as fine as the teacher thinks, because, having a mental picture of the scenery shown on a slide, he sees on the screen much more than the student can. Without doubt, every collection would be greatly improved if many of the slides were destroyed.

The Geological Division of the National Research Council, 1701 Massachusetts Avenue, Washington, D. C., has a complete file of the catalogues of foreign dealers in lantern slides and will give the addresses of such to correspondents.

TOPOGRAPHIC MAPS

Of the excellent material for the teaching of geology which the United States Geological Survey has provided, none has been more useful than Professional Paper 60, entitled "The interpretation of topographic maps." The first edition of this monograph has long since been exhausted, and, unfortunately, long before many colleges and universities had secured enough copies for class-room use; but a second edition has recently appeared and is ready for distribution.

A letter from the Director of the United States Geological Survey states that geographic descriptions of a set of 100 of the more recent contour maps that illustrate specific physiographic features "is contemplated and is being undertaken by the Physiographic Committee" of the United States Geological Survey. A preliminary circular which lists the various physiographic features represented on the different maps of this set indi-

cates that when the publication describing these maps appears teachers of geology and physiography will have a long-desired and useful addition to their teaching equipment.

Prof. A. C. Lane offers the following suggestion, which is worthy of careful consideration:

"I should welcome as a United States Geologic Survey bulletin a catalogue raisonnée of their illustrations which one could bind with blank pages interleaved, and which should be in the form of a dictionary of geologic terms with references to good illustrations of the same. If a first edition of such a bulletin could be issued and then all interested be invited to contribute to a second edition in which published or unpublished material especially illustrating words or ideas not well illustrated in the first should be included, it would be *very helpful*. If there were objections to the United States publishing this, the Geological Society of America might well publish the additional material as a supplement at its own expense."

MOVING PICTURES

ANIMATED BLOCK DIAGRAMS OR CARTOONS

The most promising undeveloped field for teaching geology and physiography, and possibly the best ever offered, is moving pictures of animated block diagrams or cartoons. The possibility of this means of illustrating geology and physiography is far-reaching, and it is safe to forecast that in the near future geologic and physiographic phenomena which at present the average student fails to understand thoroughly will be made clear. The difficulty will be to find a man to make these diagrams who possesses that rare combination—a keen mind, broad field experience, artistic ability, and common sense. Prof. W. M. Davis, in this country, could do it and perhaps two or three others.

Some of the more obvious subjects are these:

(1) Let animated block diagrams of a coast show the slow drowning of the region; then, on the cessation of the subsidence, let the waves cut away the headlands and form stacks, caves, spouting horns, and other characteristic forms and, in general, roughen the coast. Then, as the coast is eroded and passes from youth through maturity to old age, let the reel show the many features of interest and importance which result from marine erosion and deposition, such as the formation of wave-cut and wave-built terraces, bay-head beaches, spits, bars, tied islands, dove-tailed sediments, littoral and shoal deposits, and other phenomena which need elucidation. Let the animated cartoons next bring to the eye a slowly rising coast, with the production of a coastal plain; let the elevation then close with the formation of barrier islands, such as that on

which Atlantic City is built, and lagoons back of the islands; let the lagoons then be filled with sediment and organic matter; let the reel, later, show the erosion and final disappearance of the barrier islands and the marsh lands back of them. Let the scene close with a slight submergence and the production of a coast like that of Virginia and North Carolina.

(2) Most students of elementary geology have difficulty in recognizing regions in youth, maturity, and old age. A moving picture showing a region passing through these stages could be shown and would be most helpful.

(3) A moving picture of the geological history of the Appalachian Mountains would first show the deposition of sediment in the geosyncline; then the earth's crust slowly yielding to pressure and the folding of the sediments; a slow emergence from the sea; a halting, with, perhaps, peneplanation; after erosion a further submergence and deposition; then elevation, peneplanation, and the warping of the peneplain; the intrenching of the streams and the final reduction of a part of the region to a second peneplain. In other words, it should reproduce as nearly as possible the history of mountains of the Appalachian type.

(4) Diagrams showing the flooding of the Connecticut Valley as New England was lowered during the Champlain epoch, the filling of the valley with sediment, the raising of the land, and the formation of rock-defended and other terraces would be welcome.

(5) The formation of faults, with fault-line topography, and the gradual obliteration of the fault-scarps by the agents of weather and erosion could be shown on the screen.

(6) A motion picture of an igneous intrusion working its way toward the surface by stoping and melting; the formation of a volcano; the extinction of the volcano and the birth of others from higher points of the injected body would be extremely valuable.

(7) A motion picture of the geologic history of the Hudson River would be of interest to a great many people, as one-twelfth of the population of the United States is said to be within a radius of 25 miles of the Statue of Liberty.

(8) Animated diagrams of mountain glaciers, particularly showing erosion and deposition and the carving of mountain scenery, would be largely used.

(9) Many other subjects which lend themselves to this treatment will come to your minds, such as the origin and accumulation of oil and gas and its exhaustion; the formation of coral islands by both Daly's and

Darwin's theories; the mechanics of ore deposition; the evolution of Karst topography; and the story of artesian water.

Objections will immediately be offered to such cinematographs:

(1) It will be said that errors will be perpetuated in this way. But is it not more probable that if the animated diagrams are incorrect some keen geologist will soon discover this? Nothing could be more fatal to faulty reasoning than such a demonstration.

(2) A second objection will be that no one will undertake the arduous task of making the drawings for such films. The answer to this objection is that, given sufficient remuneration, some one, at some time, will be found, if the results are believed to be worth while.

(3) Another objection offered will be that such an enterprise can not be financed. Great sums of money are being expended for education, and it is not unreasonable to suppose that some of this economic surplus can be diverted to this useful end. There is also the possibility that a moving-picture company will care to finance films that will appeal to the general public.

The graduate student who has acquired a fundamental knowledge of the principles of geology and physiography and who has become skillful in drawing block diagrams can with one successful film quickly become well known, not only in the United States and Canada, but in the universities of the world.

Two attempts at such moving pictures have been brought to the attention of the committee; one is a film entitled "The story of sulphur." In this there is an animated cartoon showing how sulphur is melted out and lifted to the surface by means of hot water. The other is a petroleum picture, which the Standard Oil Company has had made, in which animated cartoons show the occurrence of oil and the method of drilling through the rocks to reach the petroleum-bearing strata. These pictures, while not of great value from the geological standpoint, serve to indicate that, with proper planning and skill, it ought to be possible to make pictures that will be excellent media for conveying instruction.

MOVING PICTURES OF SCENERY

In a recent number of *Engineering and Mining Journal*¹⁰ is the following suggestion, which is well worth serious consideration:

"Many of the geological processes could be shown on the moving-picture screen so effectively that no student would fail to grasp the idea, nor would he fail to pass an examination upon it. It would be interesting to see if the cunning devices of the machine could not also be utilized to make geological

¹⁰ *Engineering and Mining Journal*, August 20, 1921, p. 283.

changes more vivid for the advanced student and for the man of general culture. We are all familiar with the device whereby a bud blossoms into a flower on the screen before one's eyes, the pictures having been taken at slowly spaced intervals by an automatic timing device. Could not this be applied to geology, and thus forever do away with the popular belief in the everlasting hills?

"Where an island of sand and gravel is being attacked by a marine or river current, for example, and within a day or a week or a month is totally destroyed, the cinema could show it to us, dissolved in a minute. Where, after heavy rains, a deep gorge is worn within a few days in some gravel deposit, the machine would show it cut out as by a knife cutting into cheese. It is difficult to foresee the lengths to which this demonstration could go. Doubtless it would be too much to expect that photographs could be taken of glaciers at regular intervals over a number of years, and then speeded up, showing us the ice actually in the motion of flow."

When a teacher sees an unusually fine bit of scenery in a motion-picture theater he wonders if he could profitably use the picture in his class in geology or physiography. As a result of such queries an organization, called "The Society for Visual Education," has planned and produced films for educational purposes, not only for physiography, but for history, civics, health and sanitation, mathematics, nature study, and physics as well. In the film entitled "The study of a mountain glacier," President W. W. Atwood gives a "chalk talk" in which he tells on the screen the story of glaciers and icebergs, moraines, glacial valleys, etcetera. The rent asked for this film is very reasonable, but how successful the film is has not been learned. The fact, however, that the Society is sponsored by well-known geographers is evidence that the films serve a useful purpose.

RESTORATIONS

No elementary student of geology can, with any degree of satisfaction, reconstruct from their skeletons the external forms of extinct animals. Because of this fact most teachers of historic geology have found it necessary to show students not only the restorations of the skeletons of the animals of the past, but also restorations of the animals as they looked when alive. Many of the notable plaster restorations which have been made by the staff of the American Museum of Natural History are sold to educational institutions at a surprisingly low cost—an unselfish and wise policy which other museums might well follow. The museum also furnishes lantern slides of its restorations. There are also the excellent restorations of Dean, Gilmore, Gidley, Lull, Scott, and Williston in this country and those which appear in Hutchinson's "Extinct monsters and creatures of other days"; Knipe's "Nebula to man," Jaekel's "Wier-

beltiere," and a few others. A few poor plaster restorations are offered for sale in England and Germany, but they are so inferior to those made here that they may be disregarded.

Unfortunately, restorations of fossil invertebrates are not numerous and few can be purchased. The New York State Museum in Albany has on exhibition some superb restorations of graptolites, eurypterides, cephalopods, and other invertebrates, constructed under the direction of J. M. Clark and Rudolph Ruedemann. These are, without doubt, the best that have ever been made, but, unfortunately for the teaching of invertebrate paleontology, duplicates can not be purchased. Lantern slides of these can, however, be made from illustrations in the New York State Geological Survey Reports. A few restorations of invertebrates can be purchased from Ward's Natural History Establishment.

GEOLOGICAL SPECIMENS

No practical method has been discovered by which specimens which show structures, such as veins, folds, dikes, etcetera, and the effects of weathering on different types of rock under different climatic conditions can be distributed by colleges and universities. The trouble and expense involved renders this service difficult, although the replies to the questionnaire indicate that a few teachers are ready to make exchanges. Educational institutions are, consequently, obliged to depend on what they themselves can collect; on what they can purchase from dealers (usually unsatisfactory), and on what they can obtain from the United States Geological Survey and the United States National Museum.

Few aids to the teaching of geology have been productive of better results than the sets of rocks which were distributed to educational institutions by the United States Geological Survey some twenty years ago and which were described by J. S. Diller in United States Geological Survey Bulletin Number 150, 1898.

The sets of specimens showing weathering of rocks which are now being distributed to educational institutions by the United States National Museum on application, accompanied by the endorsement of a United States Senator or Representative, are excellent for teaching purposes.

RECOMMENDATIONS

The committee submits the following recommendations:

1. Since considerable apparatus can be advantageously used in advanced courses in geology and some in elementary courses, it is recommended that the teachers in graduate schools of geology, and members of

the Geophysical Laboratory, and the United States and Canadian Geological Surveys get together and determine what apparatus should be made. After a definite list has been determined on, the first cost of construction could be divided among all and duplicates sold directly at cost, or by a dealer, if it is found that some firm can produce them cheaply and well.

2. It is recommended that the following ten geological models be constructed, preferably six inches wide and less than two and a half feet long:

(1) A section of the Coastal Plain of Alabama or Texas, to show sedimentation, cuervas, and peneplains.

(2) A section of the Piedmont Belt, to show foldings, intrusions, and peneplains.

(3) An east-west section of the Appalachians, to show folding, faulting, and peneplains.

(4) An east-west section of the Great Plains, beginning with the upturned beds of the foothills of the Rockies.

(5) East-west sections of the southern Rockies.

(6) An east-west section of the northern Rockies.

(7) An east-west section of the Great Basin.

(8) An east-west section of the Sierra Nevada.

(9) An east-west section of the Great Valley of California and Pacific Coast ranges.

(10) An east-west section across the Hudson Valley from New York City to the Highlands of New Jersey.

It is also hoped that Hudson's model of Valcour Island, some of the Field Museum Geological models, some of the Canadian Survey relief maps by Dowling, and that by Adams will be produced commercially.

3. It is recommended that relief maps be constructed to show the evolution of mountain scenery by glaciation; to show stream capture by subterranean drainage, by planation, and by headward cutting of streams; and to illustrate other subjects.

4. The advantage of moving pictures of animated block diagrams is so evident and the possibilities are so far-reaching that attention is particularly called to this new method of teaching geology and physiography. Any one who has the ability to do so is urged to begin the work because it is firmly believed that such films will be more eagerly sought after than almost any other material in teaching.

5. Attention is also called to the desirability of an illustrated dictionary of geological terms with references to other good illustrations.

6. It is recommended, first, that a vertebrate paleontologist be appointed by the Society to bring together a full set of the best restorations of mammals, reptiles, amphibians, and fishes; second, that an invertebrate paleontologist be appointed to bring together a set of the best restorations of invertebrates; third, that a paleobotanist be appointed to collect the best restorations of plants; and, fourth, that a committee consisting of these three arrange with some dealer in lantern slides to offer sets of lantern slides of these lists of selected restorations of the life of the past.

7. No better way of securing specimens than by collection, exchange, and purchase has been found.

It is fully realized that the above recommendations, if adopted, will not solve all problems in the teaching of geology, because, after all is said, the teacher and his personality are more important than physical equipment; but it is believed that if these recommendations are followed much good will be accomplished, whether the teacher be good or poor.

Read from manuscript; illustrated by lantern slides.

Discussed by W. M. Davis.

DISCUSSION

Professor DAVIS: Models and other geological apparatus are, without question, helpful in teaching, especially if they are used not simply to illustrate expository and explanatory statements by the lecturer, but also to serve as the basis of laboratory work by the students. For the latter purpose each model or piece of apparatus should embody a definite problem, the solution of which should involve, first, a study of the model; second, more or less mental exercise on the facts discovered by such observational study; and, third, a written report on the facts and the results reached by mental exercise. Problems may be graded as elementary or advanced. For example, the beautiful model made under the direction of Alexander Agassiz for the Harvard University Museum by G. C. Curtis, representing Borabora, a dissected and embayed volcanic island encircled by a barrier reef in the Society group of the South Pacific, on a horizontal and vertical scale of 1:3,600, is so admirably accurate that it may well serve as a basis for attentive observation and written description by undergraduate students, and as a basis for serious theoretical discussion by graduate students. For the latter, the problem may be stated as follows:

Given, a general knowledge of volcanic processes, subaerial erosion, marine abrasion, movements of elevation and depression, changes of ocean level during the Glacial period, and the limiting depths of coral growth; draw and explain a series of sections or block diagrams (preferably sections of a cone) illustrating the changes that have occurred from the completion of Borabora as a symmetrical cone of eruptive growth to its present form, with due regard to various coral-reef theories; and state your reasons for preferring any one of those theories over its competitors.

Such an exercise is, even after hearing a lecture on the origin of coral reefs, fully worthy of the most earnest graduate student; and, moreover, until such an exercise is worked out as rigorously as if it were a geometrical theorem, even the most earnest graduate will not have mastered the coral-reef problem. In my opinion, it is chiefly because good models make it possible to introduce serious problem work into geological teaching that they are to be recommended.

Any model that is not susceptible of use as the basis of a laboratory problem is hardly worth its cost, unless the cost is very low. On the other hand, even if susceptible of such use, a single model is not ordinarily worth a very high cost, because the payment of a high cost for one model means that many other models are excluded. The model of Borabora above referred to is a magnificent adornment of a museum; but, in size as well as in cost, it far exceeds the limits that can ordinarily be allowed for geological teaching. A smaller, simpler, and cheaper model might serve very well as the basis of the two exercises above outlined; and then, for educational purposes, the cost of one large and very expensive model could be divided among many simpler but very useful models.

The model illustrating two faults in horizontal strata, shown by Professor Cleland in a lantern slide, is more useful in its geometrical than in its geological relations, for it tends to perpetuate an obsolescent geological habit of studying underground structure while neglecting surface form. Such a model may serve for a mining engineer, but it is not enough for a geologist. If used as shown, it should be supplemented by laboratory exercises in which the student has to draw sections and maps illustrating various stages of surface erosion on the faulted mass, and these stages should be extended past the first cycle of erosion on the faulted mass, at the end of which the baseleveled fault has lost its control of surface relief and is expressed only by a difference of soil on the two sides of its trace; and the later stages should include, at least for advanced students, those of a second cycle of erosion after uplift without renewed faulting, when the fault will be topographically redeveloped in a fault-line valley or in a resequent or an obsequent fault-line scarp; and the various striking differences between such fault-line features and true fault-scarps should be carefully written out. Without such extension of the exercise, the model is not used to its full value and the subject of faults is not treated with a sufficiently serious discipline. If the model be constructed so that surface parts may be successively removed to illustrate various stages of erosion in a first and a second cycle after faulting, so much the better.

As to dip and strike, I am persuaded that if there is any difficulty whatever in the teaching of such simple matters, it is due either to ignorance of geometry on the part of the student or to inexperience in explanation on the part of the teacher. In the latter case it may be that the teacher expects the student to attach ideas to the words "dip" and "strike." Such a procedure nearly always results in more or less mental confusion on the student's part. On the other hand, if the words "dip" and "strike" are not mentioned, but instead the facts of occurrence regarding tilted rocks are simply described in lectures, or illustrated in the laboratory, or studied in the field, until they become so familiar that the rock attitudes are easily talked about by the student in words of his own choosing, then he may replace his own words by dip and strike without any mental difficulty.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE MORNING
SESSION AND DISCUSSIONS THEREON

There being no further business to transact, the regular program was taken up, the first paper being

GLACIATION OF NEW HAMPSHIRE

BY JAMES WALTER GOLDTHWAIT

(Abstract)

This paper summarized present knowledge of the Pleistocene history of New Hampshire and drew conclusions regarding (*a*) the extent and thickness of the last ice-sheet; (*b*) its course across the State and the relation of this to topography; (*c*) the dispersion of stones in the drift and the survival of different rock types during transportation; (*d*) the localization of drumlins and other types of drift; (*e*) the manner and rate of recession of the ice-border, as recorded by glacio-marine, glacio-lacustrine, and glacio-fluvial deposits in the coast district and in the larger valleys of the interior; (*f*) the extent and amount of later glacial uplift and of other changes of level subsequent to it; (*g*) the questional character of alleged evidences of interglacial epochs and of pre-Wisconsin glaciation in New Hampshire; and (*h*) the date and extent of local mountain glaciation. Attention was called to certain problems which seem quite capable of settlement, and to others upon which we seem as yet to have no light.

Presented in abstract from notes, with lantern-slide illustrations.
Questions were asked by J. L. Tilton and J. B. Woodworth.

*RECESSION OF THE LAND-ICE IN NEW ENGLAND*BY ERNST ANTEVS¹*(Abstract)*

In 1921 the recession of the land-ice in New England was studied by Gerard De Geer's method² of measuring the varve (annually laminated) clays and silts. The fields covered are the Connecticut Valley from New Haven to the Canadian frontier and the Merrimac Valley around Concord, New Hampshire.

Glacial varve-clays are exclusively deposited in fresh or almost fresh water; in salt or strongly brackish water more or less homogeneous clays are formed, such as those, for instance, that occur in the coast regions of New Hampshire and Maine. There being beautiful varve-clays at Hackensack, New Jersey, more than 15 feet below sealevel and at New Haven, Connecticut, more than 25 feet below the sea, it is evident that these regions or, as I think, the peripheric zone of (the eastern part of) the glaciated area, quite in Europe, took a higher vertical position, when it was relieved of the ice, than it

¹ Introduced by Edward B. Mathews.

² Gerard De Geer: A geochronology of the last 12,000 years. *Compte rendu du XI; e congrès géologique international*, p. 241. Stockholm, 1912.

does nowadays, the sealevel being regarded constant. That the southern Hudson region at that time was elevated was vindicated by J. B. Woodworth³ on physiographic evidences already in 1905.

Thus, when the land-ice receded from New England the southern part was somewhat elevated, whereas the rest of the region was submerged, and the more so the farther one comes northward. As a result, series of lakes were ponded off the ice-edge as it withdrew. In these lakes the varve sediments were deposited. A great number of profiles were measured in clay-pits and natural exposures. One measurement overlaps the other, and the principal result is an almost continuous series of annual layers registering the recession of the ice-edge from Hartford, Connecticut, to Saint Johnsbury, Vermont.

The material is not yet sufficiently worked up to permit me to give exact figures, and to publish approximate ones does not seem appropriate. However, the retreat of the ice-edge from Hartford to Saint Johnsbury took some thousands of years. The recession was interrupted by some halts and readvances, but on the whole it gradually increased from less than 200 feet a year in northern Connecticut to about 1,000 feet south of Wells River, Vermont.

Presented extemporaneously, with lantern slides.

Discussed by J. F. Kemp, who gave a brief description of the technique of the De Geer Method of investigating the laminated clays; by J. W. Goldthwait, who spoke of the immense volume of data collected in the last seven or eight months, and by H. F. Reid and Frank Leverett.

STRUCTURE OF THE CONNECTICUT BASIN DURING THE NEWARK EPOCH

BY WILBUR G. FOYE

(Abstract)

Among the most important unsolved problems of the Connecticut Triassic basin is the question of the nature of the depression within which the Newark sediments accumulated. Two diagrams of the conditions which initiated the sedimentation are most frequently given in the textbooks. The first, by Davis, shows the depression to be due to the downwarping of a peneplaned surface. The second, by Barrell, indicates that the depression was developed by the tilting of a monoclinical fault-block. In his original paper, Professor Davis recognized that the graben theory for the origin of the valley was possible; but, in the absence of conclusive evidence, the diagram was constructed to show a warped peneplain. The writer believes there are strong reasons why the diagram by Barrell should supersede the more widely recognized diagram by Davis.

Presented from notes, with lantern slide illustrations.

Discussion was participated in by W. J. Miller, J. B. Woodworth, W. M. Davis, C. E. Gordon, C. R. Longwell, H. B. Kümmel, W. N. Rice, and L. S. Westgate, with reply by the author.

³ J. B. Woodworth: Ancient water levels of the Champlain and Hudson valleys. New York State Museum, Bull. 84, p. 229. Albany, 1905.

DISCUSSION

Professor MILLER: From my own observations in the vicinity of Northampton, Massachusetts, I am certain that there has been downfaulting of thousands of feet on the west side of the valley as well as on the east, as shown by the fault-scarp and great crush zone in the city quarry of Northampton; also, there is evidence for very considerable former extension of the Triassic, both east and west of the present valley sides. For these reasons I believe that the principles involved in all of the first three of Professor Foye's sections should be combined by considering very appreciable downwarping at first, and then trough faulting (possibly caused by loading of sediment), with generally the most profound downward movement on the east, thus accounting for the usual eastward dips.

Professor WOODWORTH remarked that, in contrasting sediments on the eastern and the western sides of the Connecticut Valley in Connecticut, comparisons relate generally to the top and bottom of the Triassic respectively.

Professor DAVIS said that he felt much satisfaction at the progress of Professor Foye's work on the Connecticut Triassic and expressed the hope that it might be continued, especially in the direction of searching for new localities of upper contacts between the lava sheets and overlying sediments; for new outcrops of fossiliferous black shales both anterior and posterior to the main trap sheet and at new horizons; for new examples of shales slickensided on bedding planes, as if the result of a sliding accommodation to the warping of faulted blocks; for additional evidence by which the trace of faults can be followed in the Triassic area; and, most important of all, for new evidence of the continuation of the Triassic faults into the eastern and western highlands of crystalline rocks. As to the modifications suggested by Professor Foye in the speaker's hypothetical cross-sections, published over twenty years ago in his report to the U. S. Geological Survey, a diagram is always a venturesome means of representing a hypothetical condition, because it is necessarily definite, while the hypothetical condition is preferably vague and shadowy. The proposed modifications in the diagram are therefore interesting and welcome. A fault along the western margin of the Triassic might probably be introduced to advantage in certain districts, but whether such a fault was produced during the deposition of the Trias or afterwards, or both, is not easily determined. The speaker closed by saying that in any case it was a satisfaction to see that he had suffered more from his diagram than from his ideas.

Professor GORDON: In favor of pre-Triassic faulting in the formation of the Newark basin, I have been impressed with the coarseness of the material along the eastern border, at least in Massachusetts, which it has seemed to me offers suggestion of steep slopes which might well have been favored by fault displacements. It is plain that in any attempt to account for the configuration of the Newark basin by faulting care must be exercised not to confuse displacements of very different age and therefore of very different significance.

Professor LONGWELL: Extreme coarseness and angularity of material are prominent characteristics of the Triassic near the eastern fault boundary in southern Connecticut. The "boulder ridges" north of Branford, accurately described years ago by Dana and Hovey, are made up of the most typical

fanglomerate I have seen outside of the Great Basin. The materials came from the east, evidently from very steep topography, and the presence of vesicular basalt boulders indicates that one of the lava sheets extended east of the fault zone. The upper (posterior) sheet was poured out while the fanglomerate was accumulating, for the sheet thins and apparently wedges out in the coarse deposits. Recurrence of faulting is suggested by the presence of coarse fan deposits at several horizons, and by the presence in the fanglomerate of distinctive material from quartz veins that parallel the fault zone. Very possibly these veins mark the location of earlier faults, and, during later movements the veins themselves have been faulted and shattered.

Dr. KÜMMEL: The Triassic trough in New Jersey is in many fundamental respects like that of Connecticut and Massachusetts. Since the dip is to the west and not to the east, the eastern margin in New Jersey corresponds to the western in Connecticut. In New Jersey, as in Connecticut, arkose beds occur along the margin from which the beds dip, while coarse conglomerates characterize the other margin. These conglomerates were found by streams capable of transporting boulders upward of a foot in diameter. The western margin of the trough in New Jersey is a fault border, the faulting probably having been progressive during the Trias and at its close.

Professor RICE: I can well believe that no one of the three hypothetical sections of the Connecticut Trias exactly represents the actual history. I can well believe that, as has been already suggested in this discussion, there may be an element of truth in each of the three hypotheses. There is no absolute distinction between a fault and a flexure, between a graben and a geosyncline, since a breaking is apt to begin with a bending. Nevertheless, I am inclined to believe that the Barrell-Foye hypothetical section is nearer to the exact truth than either of the two sections suggested by Davis. On the graben hypothesis—the hypothesis that the depression in which the sedimentation took place was due to faults of approximately equal throw on the two margins of the formation—all the strata should have been approximately horizontal at the time when the present monoclinal dip was developed by movement following the close of the deposition. On this hypothesis, therefore, the present dips should be equal on the two sides of the area. On the Barrell-Foye hypothesis, at the close of the period of deposition the older beds on the west side of the valley should have had a dip to the east, while the newer beds on the east side should have been nearly horizontal. On this hypothesis, therefore, the western side of the formation should now have a slightly steeper dip than the eastern. On the geosynclinal hypothesis, the beds on the east side of the formation should have had a westerly dip at the close of the period of deposition. On this hypothesis, therefore, the dips at present should be decidedly steeper on the west side than on the east side. The actual dips on the east side range in general from 15 to 20 degrees; those on the west side from 20 to 25 or 30 degrees. While these facts do not afford a basis for a positive conclusion, they seem rather favorable to the Barrell-Foye hypothesis. On the geosynclinal hypothesis, apparently, the difference of dip should be greater. On the graben hypothesis, there should be no difference.

Professor WESTGATE: If the Newark beds are largely subaerial, can we assume that the beds were originally horizontal, or must we not assume an initial dip from each side toward the axis of the basin which may be in part at least responsible for the present difference in dips on the opposite sides?

GEOLOGY OF COSTA RICA

BY E. B. BRANSON

(Abstract)

The dominant topographic feature of eastern Costa Rica is a high mountain range that trends northwest-southeast. The country east of this range is made up of piedmont alluvial fans. In a few places remnants of Cenozoic sedimentaries are preserved. In the valley of the Reventazon River the Cenozoic sediments are more than 10,000 feet thick and range from Eocene up in age. The dominant activity of recent times has been vulcanism, and nearly all of the sedimentaries are extensively intruded by recent lavas. Volcanic ash deposits of Pliocene or Pleistocene times are widespread. The seas seem to have extended across this region during most of the Cenozoic. Some of the formations are highly fossiliferous.

Presented extemporaneously, with lantern-slide illustration.

Adjournment was taken about 12.30 o'clock p. m.

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE AFTERNOON
SESSION AND DISCUSSIONS THEREON

The Society divided into two sections Wednesday afternoon. The first was presided over by Vice-President Woodworth, and Edmund Otis Hovey acted as its Secretary. The following program was offered:

THE ANDEAN GEOSYNCLINE

BY CHARLES SCHUCHERT

(Abstract)

The nature of the Andean geosyncline and of the old land that lay to the west and is now sunken into the abyss of the Pacific was briefly described and contrasted with that of the Appalachian geosyncline. These two geosynclines, with their periodically rising bordering lands, are markedly different in their quantitative movements.

Presented extemporaneously.

Discussed by F. P. Shepard, W. M. Davis, K. F. Mather, T. Wayland Vaughan, and W. H. Bucher.

DISCUSSION

Dr. SHEPARD: Might I ask Professor Schuchert whether it would not be possible for the forelands to be much narrower than 250 miles and still produce the required amount of deposits in the geosyncline by being constantly uplifted? In this way a less important change of the ocean floor would be required to produce the present configuration.

Professor DAVIS asked why so small a limit as 250 or 500 miles was set for the width of the Atlantic foreland of the Appalachian belt. Such a width

might be assumed for the part of a land area which sloped toward Appalachia, and from which, by reason of continued elevation and erosion, a sufficient volume of detritus would be supplied to form the Appalachian sediments; but in that case an additional width of land should be imagined farther to the east and sloping in that direction into the Atlantic. As to guiding restorations of former land and water areas by the assumption that the volume of the ocean has been constant since the beginning of Paleozoic time, that is probably the easiest assumption to make, but it does not seem to be the most probable. In view of the enormous discharge of water from volcanoes, it is conceivable that the volume of the oceans may have undergone a large increase during the long continuation of volcanic activity, here and there, now and then, over the earth; if the contemporaneous hydration of newly exposed rocks has not withdrawn water as fast as volcanic eruptions supplied it, the early oceans may have been much smaller than the present oceans. In our present ignorance on this subject, the assumption of a constant oceanic volume should be regarded as only one of several permissible assumptions.

Dr. MATHER: The crumpling of the strata accumulated in Devonian and earlier Paleozoic time in the Andean geosyncline occurred at the close of the Devonian period, from which time the eastern Andes have been in large measure a positive rather than a negative element of the continent—crumpled Devonian sediments overlain unconformably by Permian and younger terrestrial strata. Evidence is lacking in central Bolivia of mountain-making movements at the close of the Paleozoic era.

Dr. VAUGHAN inquired if Professor Schuchert would rule the so-called Himalayan geosyncline out of the category of geosynclines. He replied that he would.

Professor SCHUCHERT: Doctor Bucher is correct in saying that Haug wanted to show, among other things, that the geosynclines are the most labile regions of the earth's surface. Haug's paper is undoubtedly one of the classics in stratigraphy and has stimulated further research as to the geologic work done in geosynclines. On the other hand, his main studies are not based on a true geosyncline—the Appalachian one is the typical geosyncline—but on a mediterranean. The latter is a labile area, a long and narrow and very deep waterway lying between two continents—Europe and Africa, for example—while a true geosyncline is a labile, very shallow-water area within a continent. On one side of the Appalachian geosyncline lies the unmoved Canadian shield or neutral area of the North American continent, while its other and oceanward side is the rising and inwardly moving geanticline, the Appalachian foreland. The stratigraphy, petrology, and faunas, and especially the tectonic results, are very different when the records of geosynclines are contrasted with those of a mediterranean like the Roman one, or, better, Tethys.

STRUCTURAL RELATION OF THE PURCELL RANGE TO THE CANADIAN ROCKIES

BY FRANCIS P. SHEPARD¹

(Abstract)

The Purcell Range of British Columbia is separated from the Canadian Rockies by the deep, narrow Rocky Mountain trench. The structural geology

¹ Introduced by Rollin T. Chamberlin,

in the vicinity of the trench was studied from Elko, just north of the international boundary, to Golden, 180 miles to the north. Because of its location, the valley offers an excellent opportunity to examine the structure of the flanks of the two ranges and the structural relation of these two ranges to one another.

Two distinct zones were found to exist in the 180 miles. One of these extends 90 miles, from Golden to Canal Flats. In this section there are thrust-faults on both sides of the trench and in some cases within the trench itself. On the west side these faults have westward-dipping planes and on the east mostly eastward-dipping planes. The thrust-faults from the west are more pronounced than those from the east, resulting in an older series of rocks on the west side of the trench. Slaty cleavage, which dips to the west on the west side of the trench, becomes vertical toward the center. Where observable on the east side, it dips to the east. These structures dipping into the range are evidence in favor of R. T. Chamberlin's hypothesis of wedge-shaped deformation in mountain-building. These two ranges represent the intersection of two wedges. This part of the valley has been located by the resulting line of weakness.

South of Canal Flats the line separating the structure of the Purcell Range from that of the Rocky Mountains leaves the trench and swings to the east, being as much as 15 miles from the valley in some cases. In this part of the valley, which extends for 60 miles to the south, the trench does not follow structural lines. The great width of the valley and the evidence for a Cretaceous peneplain over the sight of the Purcell Range suggests that the valley developed originally on an old erosion surface and persisted in its location, even though the zone of weakness developed near at hand to the east during the later deformative movements. Thus, in this portion of the valley the structural separation of the ranges is not shown by the relief.

Presented extemporaneously.

Discussed by W. M. Davis, who raised a point as to the author's use of the term "trench" as being unusual.

*FAULTS, UNDERDRAG, AND LANDSLIDES OF THE GREAT BASIN RANGES*¹

BY W. M. DAVIS

Gilbert first assumed that the faults on which the crustal blocks of the Great Basin mountain ranges have been uplifted were essentially vertical. He and others later described the aligned spur-end facets along the base of the steeper side of certain ranges as representing parts of the fault-planes on which the range blocks were raised. But the moderate slope of the facets gives so large a hade to the fault-planes (55 or 60 degrees) as to imply a greater horizontal than vertical movement at the time of displacement; and in that case it would seem better to describe the ranges as the result of horizontal extension than of vertical upheaval. Gilbert's latest expression of opinion in this matter was made in connection with a discussion of the depth at which crustal underflow takes place in the reestablishment of isostatic equi-

¹ Manuscript received by the Secretary of the Society in January, 1922.

librium after it had been disturbed. It deserves more consideration than it has received. The case of compression was first stated:

"In some regions, such as the Appalachian, overthrusts and folds testify to great reduction in the horizontal extent of rocks at the surface, the reduction having been accomplished in a small fraction of geologic time. If the subjacent portion of the nucleus had been correspondingly forced into narrower space, there would have resulted an enormous mountain range, but the actual uprising was of moderate amount. Plausible explanations of the phenomena necessarily include horizontal movements of the upper rocks without corresponding movements of the nucleus, and thereby imply mobility of an intervening layer."

The case of extension is then taken up:

"In certain block-mountain districts of the West the master faults are antithetic in type to the overthrust and demonstrate pronounced extension of the upper part of the crust. The nucleal tract beneath could not share in this extension without creating an enormous depression, which does not exist; and the interpretation of the phenomena involves horizontal shear in material more mobile than the visible upper rocks."²

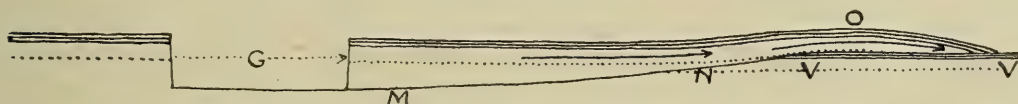


FIGURE 1.—An Overthrust, *O*, leaving a Cavity, *G*, behind it

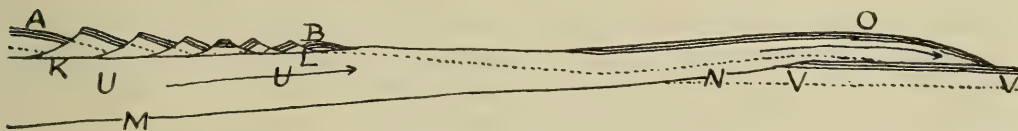


FIGURE 2.—An Overthrust, *O*, emerging from beneath the Crust, *AB*, which is displaced and extended by "Underdrag"

If this interpretation be correct, we may be led to regard the area of the Basin ranges as filling a long-felt want in representing the "other side of an overthrust," and as therefore showing the effects of what may be called, for want of any other name, an "underdrag." This may be hypothetically if not fantastically illustrated by figures 1 and 2. On the right, *VV* is a passive part of the crust that has been covered by an overthrust, *O*. Let the overthrust mass be followed back toward its source. It should presumably be found to rest on a slanting undersurface, *MN*, on which the advancing ascent of the overthrust for one or two score miles, as represented by long arrows, took place. As to the upper surface of the overthrust, had its backward extension not dipped underground, it must have somewhere left a vast gap, *G*, figure 1, where it withdrew from that part of the crust which was not involved in the overthrusting; and as no such gap is anywhere known, it appears advisable to change the supposition that the backward extension of the upper surface of the overthrust did not dip underground into the opposite supposition that it did dip underground, as in figure 2. Thus interpreted, the advancing, over-

² Interpretation of anomalies of gravity. U. S. Geol. Survey, Professional Paper 85-C, 1913, p. 35.

thrusting mass must be conceived as emerging from beneath the surface at B and as being separated from the surface crust, BA, by another slanting surface, KL, similar to the undersurface, MN. It is particularly with the phenomena of underdrag, where the root UU of the advancing mass is driven along beneath the passive crust, AB, that we are here concerned; the underdrag ought to break up this part of the crust into slabs and blocks on oblique fractures, and each block ought to be dragged along and more or less displaced and tilted by the advance of the root of the overthrust; and such a displacement and tilting of the blocks might give rise to the Basin ranges, if they are really characterized by horizontal extension instead of by vertical upheaval. This is of course deeply fantastic, as there is no direct warrant for accepting the existence and movement of such a mass as the root of an overthrust, UU, between the passive masses below and above it; but inasmuch as the occurrence of overthrusts at the surface is now a well established fact, and inasmuch as Gilbert's latest interpretation of the Basin-range displacements suggests the operation of what is here called underdrag, it is perhaps permissible to inquire into the possible connection of the two phenomena by continuing the overthrust backward underground toward its root. It is manifest, however, that the ultimate root or source of the overthrust mass is not reached in figure 2.

But there is another interpretation of the displaced Basin-range blocks which involves vertical upheaval, as Gilbert originally thought, rather than horizontal extension, as he later thought. It may be imagined that the spur-end facets, which have been regarded as parts of moderately inclined block-mountain fault-planes, are really landslide surfaces of much less declivity than that of the true fault-planes between the mountain blocks, and that great slabs of the steep-faced blocks slipped down these surfaces into the intermont depressions while the displacement was going on; for if the bounding fault of a mountain block be nearly vertical, and if the upheaval of the block be relatively rapid, the upper edge of the block might not be able to sustain itself unsupported, and great slabs of it would therefore break off and slide down on the depressed block. The uniformity of inclination in the spur-end facets would at first thought seem to discountenance this idea; but if the landslide slabs be conceived as 2, 5, or 10 miles in length along a range front, their surface of motion might be fairly regular. The rarity of visible landslides at the base of the ranges may be explained in part by their burial; but besides buried slides, the rarity of described slides may be explained in part by inattention to such slides as are still visible.

The best evidence in favor of this second view is found in the recent landslides described by Russell as occurring at the base of very young fault-block mountains in central Washington. Rattlesnake Mountain is described as "one of the most typical monoclinical mountains. . . . Its northeast escarpment is an exceeding bold bluff rising nearly 3,000 feet above the plain . . . and is formed of the broken edges of the strata of Columbia lava, which dip gently to the south and southwest and give the mountain its long, gentle, southern slope. Owing to the fact that many landslides have fallen from its precipitous northeast face, the outcrops of the beds on that side have been covered with debris and greatly obscured." Similarly in the steep scarp of Horse-heaven

plateau, about 1,600 feet high, "outcrops are largely concealed by landslides. The slides have formed many undrained basins on the face of the steep slope and also irregular lines simulating terraces. A very large portion of the details in this, as in many other fault-scarps formed of broken strata of Columbia lava, are thus accounted for. Reference to similar features in other uplifts will occur again and again as we proceed. The reason why landslides have been so numerous in the steep slope of Columbia lava . . . is because the strata are in layers separated in some instances by thin sheets of lapilli or of clay and sand, which weather out and allow large slices of the dense rock resting on them to break off." The Simcoe and Topinish landslides are described on later pages.³

The alternation of strong and weak beds described by Russell doubtless facilitates the dislodgment of slides; but they might be precipitated from massive rocks if the initial scarp were steep and high enough. The main point brought out by his observations is that landslides characterize young block mountains.

My own experience in the Great Basin is brief, but a single excursion in the summer of 1904 sufficed to discover a very large landslide at the western base of the Canyon Range in west-central Utah. The slide stands about 500 feet high for some two miles along the mid-front of the range and spreads about two and a half miles forward; but it is of so remote a date that its surface is maturely dissected by branching valleys with graded slopes and it retains no trace of the hill-and-hollow forms such as young slides commonly possess.⁴ A smaller slide was seen in the north-south Wasatch Range where it consists of a monoclinical mass of strong and weak strata dipping to the southeast; the thickest body of weak strata, along which an oblique depression is worn across the range, has "spilled" westward from the range base, as if because of a recent uplift.⁵

An earlier experience in the West tempts me to think that landslides may be more common along the base of the Basin ranges than the absence of mention of them in the brief descriptions of most of the ranges would imply. In the summer of 1900, when an excursion led me across the Colorado River at Lees Ferry, some 50 miles northeast of the Grand Canyon, a large number of huge landslides were noted along the base of the Echo cliffs and the Paria plateau for some 20 miles on each side of the river, evidently because of the removal of the weak blue clays from beneath the heavy Vermilion sandstones in the current cycle of erosion;⁶ and yet, although this district had been visited by Powell, Gilbert, and Dutton, the landslides are not mentioned by them, perhaps because the slides are subordinate to the larger phenomena that engaged the attention of those explorers; but some of the slides sprawl forward for the better part of a mile from their source, and they are easily seen and recognized at a distance of 10 miles or more from the summit of the Kaibab plateau on the west.

³ A geological reconnaissance in central Washington. U. S. Geol. Survey Bull. 108. 1893, pp. 40, 43, 47, 48.

⁴ The Wasatch, Canyon, and House ranges, Utah. Bull. Mus. Comp. Zool., xlix, 1905, p. 30.

⁵ Ibid., p. 21.

⁶ An excursion to the Grand Canyon of the Colorado. Bull. Mus. Comp. Zool., xxxviii, 1901, pp. 123-125.

Reference may be briefly made to a rock-scarp that was formed along the lower slope of the Sonoma range in Nevada at the time of an earthquake in 1915. The face of the scarp, which may be regarded as the visible surface part of the fault-plane by which the mountain mass is believed to be bounded and on which it is supposed to have been uplifted, seems to have a slope of 50 degrees at least, and movement on such a surface would partake more of vertical upheaval than of horizontal extension. If scarps of this kind occur elsewhere, and if landslides of the Canyon-range type are discovered to be less exceptional than would today seem to be the case, then it may be permissible to return more to Gilbert's early conception of the origin of the Basin ranges.

Whatever the hade of the mountain-block fault-planes is found to be near the mountain base, it is probable that it was steepest where it reached the land surface before the mountain blocks were displaced, and that it is less steep at a considerable depth below the present surface; in other words, that the fault-"plane" is a curved surface, concave to the downthrow. This opinion is based in part on a principle announced by McGee.⁷ The total surface on which a landslide moved should also be concave, or steeper above than below. Hence, even if the fault-planes are fairly steep, they should still involve some horizontal extension in connection with their nearly vertical displacements, and even a limited measure of horizontal extension would be aided by an underdrag of some such kind as above suggested.

GENERAL MORPHOLOGIC FEATURES OF BASIN RANGE FAULTS

BY GEORGE D. LOUDERBACK

(*Abstract*)

A general presentation of the morphologic features as observed in the field and related to their immediate origin, with particular reference to the following topics: size of blocks, rotation, distribution of frontal displacements, cross-faulting, longitudinal variation, and the occurrence of internal faults.

Read from manuscript.

Discussed by H. G. Ferguson and H. F. Reid.

BURIED GRANITE IN KANSAS

BY RAYMOND C. MOORE

(*Abstract*)

Following the discovery of very productive deep oil sands in Butler County, south central Kansas, in 1915 and 1916, and of oil-producing horizons within and below the Mississippian, in southeastern Kansas and northeastern Oklahoma, many deep wells have been drilled in various parts of the State. Approximately forty of these wells, up to the present time, have reached crystalline rocks, chiefly granite. A few of the "granite wells" are found in the eastern part of the State, but most of them are grouped in a line or narrow zone which extends from Pawnee County, in southeastern Nebraska, south-south-

⁷ On the origin and hade of normal faults. Amer. Journ. Sci., xxvi, 1883, pp. 294-298.

west across Kansas to a point in Cowley County not far from the Oklahoma line. Determination of the elevation of the top of the granite from the records of these wells and observations of many deep wells which have failed to reach crystalline rocks have made possible the delineation, with considerable accuracy, of the form of much of the buried granite surface.

In eastern Kansas the granite surface slopes gently westward away from the Ozark uplift, which has its eccentric high point in the Saint Francis Mountains, south of Saint Louis, where the granite is exposed. The granite is approximately 1,000 feet below sealevel at Columbus, Cherokee County, in the southeastern corner of Kansas, and nearly 1,500 feet below sealevel at Kansas City. The inclination of the granite surface in this region appears to be fairly regular and approximately equal to the dip of the overlying stratified rocks. An irregularity of considerable importance, however, appears in the vicinity of Yates Center, in Woodson County, where granite was encountered in a well at a depth of 2,585 feet, while at Iola, Allen County, about 20 miles to the east, a well 3,434 feet deep did not reach crystalline rocks, and another well, 10 miles northwest of Yates Center, was drilled to 3,557 feet without encountering the basement granite. The granite is very deeply buried in Greenwood County and in the adjacent country to the north and south.

The "granite wells" in central Kansas are located in a prominent belt of anticlinal structure, with part of which is associated the important oil and gas fields of Butler and Marion counties. The granite rises rather sharply and, as now known, has the form of an elongate ridge marked by a number of high points or peaks which are separated by intervening saddle. The highest part of the buried granite ridge is near the north Kansas line, where crystalline rocks approach to within 550 feet of the surface and attain an elevation of nearly 600 feet above sealevel. To the south there is a rather low saddle, beyond which the granite surface rises beneath Morris and Chase counties in a number of more or less prominent peaks. None of these, however, attain an elevation equal to that of the granite north of the Kansas River. In northern Butler County the crest of the ridge drops rather sharply, but rises beneath both the Eldorado and the Augusta oil fields. Farther south the granite is encountered only at increasing depths.

The lateral slopes of the granite ridge have been ascertained at some points. It appears that the east slope is considerably steeper (150 feet per mile, average) than that on the west (50 feet or less). At the present time data are hardly sufficient to support strongly the suggestion that displacement by faulting, with downthrow to the east, is responsible for the granite ridge.

Studies of the relation of the sedimentary rock formations to the granite ridge are incomplete, but it is evident that in some places rocks as young as the uppermost Pennsylvanian are in contact with the granite. In some places, chiefly in the saddles and on the flanks of the ridge, considerable thicknesses of limestone belonging to the Mississippian and Ordovician intervene. There was evidently important weathering and erosion of the pre-Pennsylvanian formations in this region before Pennsylvanian sedimentation.

The major structural features which are observed in the sedimentary rocks above the granite, as well as many of the minor anticlines and synclines, appear to be controlled by the underlying granite. The structure in general

reflects the configuration of the granite surface. To the formation of these folds, controlled by relations to the granite, is largely due the existence of the central Kansas oil and gas fields.

Presented extemporaneously, with lantern-slide illustration.

DISCUSSION

Discussed by WILLIAM BOWIE, who said that pendulum stations were to be established in the region discussed by Dr. Moore for the determination of gravity. These may lead to ability to predict presence of crystalline rock ridges.

INTRAFORMATIONAL CORRUGATED ROCKS

BY WILLIAM J. MILLER

(Abstract)

It is the purpose of this paper to enter rather fully into a consideration of intraformational corrugated rocks. Examples are discussed from formations ranging in age from Archeozoic to Postglacial. Assigned causes for the corrugations include the following: differential movements accompanying regional folding, thrust and normal faulting, and pressure of intruding magmas, compression of weaker layers between more resistant layers, differential sliding due to gravity, subaqueous gliding, differential weighting, crowding action of ice, swelling due to crystallization, magmatic flowage, and magmatic injection.

Read from manuscript and illustrated by lantern slides.

DISCUSSION

Discussed by JAMES H. LEES, as follows: Along Bayer Valley, in Crawford County, Iowa, is an exposure showing valley gravels, as described in abstract in Bulletin of the Geological Society of America, 1921. Above the gravels are intercalated bands of sand and loess which are very much contorted, while the underlying gravels are horizontal. These intercalated bands have a total thickness, as exposed, of about 3 feet. The individual bands are only a few inches thick. The cause of the contortion is in doubt, but it may be slumping down the valley walls.

STRUCTURE OF THE PRE-PENNSYLVANIAN ROCKS OF THE BIG STONE GAP AREA, WISE COUNTY, VIRGINIA

BY GEORGE W. STOSE

(Abstract)

The area is an anticlinal valley between Stone Mountain and Powell Mountain, monoclinical ridges capped by Lee conglomerate. The anticlinal rises toward the southwest and exposes Clinch sandstone, which forms Walden Ridge at the county line, and underlying rocks down to Knox dolomite to the southwest. The anticline is sharply overturned and overthrust at the center

of uplift and presents very interesting details of structure. The fold fingers into several small folds as it plunges northeast, which are also faulted. A colored map of the area and structure sections will be presented.

Presented extemporaneously.

Discussed by H. F. Reid and the author.

*RELATION OF DEEP-SEATED FAULTS TO SURFACE STRUCTURE IN THE
REGION NORTHEAST OF THE YELLOWSTONE PARK PLATEAU*

BY W. T. THOM, JR.¹

(Abstract)

This paper reviews briefly what is known concerning the great thrust-faults which feature the front of the main Cordilleran belt in Montana and Wyoming, and illustrates the structural features of the irregular uplifts of central Montana by means of structure contours drawn on the base of the Upper Cretaceous series. This structure contour map indicates the existence of marked structural trends and strongly suggests that the development of the existing surface structural feature has been controlled by fundamental faults. The existence of these fundamental faults and their geologic importance is seemingly further indicated by the areal distribution and development of certain formations and by the location of the several important areas of former igneous activity which exist in central Montana.

Presented by title.

POSSIBLE TILLITE AT LEVIS, QUEBEC

BY ROBERT W. SAYLES

(Abstract)

In the Levis shale of the Beekmantown formation at Levis, Quebec, there occurs a bed which appears to be of glacial origin. The evidence of such origin is found in the remarkable similarity to beds of sublacustrine tills and tillites intercalated in the Pleistocene glacial clays and in glacial slates and shales of older glaciations, especially as found in the glacial clay at Woodsville, New Hampshire, and at Squantum, Boston Harbor. This bed was found by the author on September 23, 1921, while on the way to examine the limestone conglomerates at Levis with T. H. Clark, of Harvard University. It can be seen in the cliff opposite the lumber yard of C. H. Jackson & Company, five minutes' walk down the river from the railway station.

Like the sublacustrine tills and tillites, this bed is composed of a till matrix in which are imbedded blocks and contorted masses of the underlying banded shale, together with boulders and rock fragments with rounded and angular and subangular shapes, lying at all angles and with no sorting or stratification visible. The bed itself is very uneven in thickness and the upper contact with the overlying shale is uneven and wavy, just as in other cases of such sub-

¹ Introduced by David White.

lacustrine tills. The lower contact is more even, as far as observed, and this is also true of similar tills in the Pleistocene and older cases. The thickness, as far as observed, varies from 8 or 9 feet to 3 or 4 feet.

A preliminary examination of the matrix with the microscope has been made by my colleague, Prof. J. E. Wolff, and the author. The matrix contains small angular and rounded grains of limestone, quartz, coarse slate, minute fragments of limestone conglomerate, chert, secondary chlorite, secondary calcite, secondary rhombohedra of dolomite, plagioclase, sericite, and a dark isotropic substance with index of refraction higher than balsam. In one fragment of this substance were found small vugs filled with chalcedony and quartz. Small fragments of fossils may be seen rarely. The cement is very fine and is composed, for the most part, of minute grains of quartz, lime carbonate, and a paste of sericite. The material of the matrix is mostly fresh and angular. The structure of the matrix differs in no way from the matrices of other tills and tillites. Very angular quartz grains constitute the most important single character, and these are common to all tills and tillites.

The shale above and below this tillite bed is most regularly banded in dark brown and gray layers. The microscope proves that the light layers have very fine clay material, usually homogeneous throughout, ending abruptly on top with the finest material of all. These fine layers are succeeded by the brown layers, composed of coarser and angular grains, mostly of quartz, but with other of the minerals found in the matrix of the tillite. The brown color is due to an infiltration of an oxide of iron which could find its way easily between the coarse grains and come to rest, but was for the most part unable to penetrate the impervious clay of the fine layers. The coarse layer has the characteristic alternations of coarser and finer materials found in the Pleistocene banded clays and also as found by the author in the Squantum slate and a number of other slates and shales. It would appear from the observations so far made that this shale at Levis has good seasonal characters.

The extent of the tillite bed is not fully known. In the limited time at our disposal it was traced only about 400 feet.

The Irasburg conglomerate, of Beekmantown age in Vermont, is thought by Prof. C. H. Richardson, of Syracuse University, to be of glacial origin. This conglomerate has been traced for 100 miles in Vermont and for 25 miles into Canada.

Read from manuscript. Illustrated with lantern slides.

STAGES OF THE ICE AGE

BY WARREN UPHAM

(Abstract)

In a review of the series of glacial and interglacial stages ascertained from the North American drift deposits, the early Nebraskan stage of glaciation is correlated with the first high-water stage of Lakes Bonneville and Lahontan, estimated by Gilbert to have been five times longer than the second and latest great rise of these Quaternary lakes. Intermediate nearly or quite complete evaporation of these lakes, during time estimated longer than the post-Glacial period, appears to be represented by the interglacial Aftonian stage of wide

recession of the ice-sheet, and the ensuing second very high stage of the lakes occurred probably during the culmination and gradual disappearance of the ice-fields. This second and less prolonged part of the Glacial period included the maximum Kansan and Illinoisan stages, with the ensuing Iowa and Wisconsin glaciation, being terminated when subsidence of the formerly high ice-covered land brought the final melting of the continental glacier, its departure being attended by the formation of very remarkable terminal and recessional moraines. Time ratios, based on studies of the Falls of Saint Anthony and Niagara by Winchell, Gilbert, and Wright, with De Geer's measurement of the late Glacial stages in Sweden, demonstrate the geologically recent end of the Ice Age and suggest for its entire duration an estimate of about 250,000 years.

Presented by title in the absence of the author.

GLACIAL FORMATIONS ON THE COTEAU DES PRAIRIES .

BY FRANK LEVERETT

(Abstract)

The Coteau des Prairies leads from the head of Big Sioux River, in South Dakota, southeastward across southwestern Minnesota into Iowa, and finds its natural continuation across Iowa in the high divide between the Missouri and Mississippi drainage. The crest is about 2,000 feet above sealevel in South Dakota, but declines southeastward to about 1,600 feet at the Minnesota-Iowa line and to about 1,300 feet in southern Iowa. The highest known altitude of rock formations along it is about 1,700 feet; but this altitude is attained in only a few places, usually where the Sioux quartzite is prominent. Along much of its course the glacial deposits are 500 to 700 feet thick. In western Iowa they range from 300 to 700 feet.

The Coteau is so situated as to embrace the younger as well as older drifts. The Wisconsin drift reaches a little beyond the crest of the Coteau in South Dakota and Minnesota, but falls a little short of reaching the divide in Iowa. This drift forms but a small part of the glacial material, probably an average of less than 50 feet.

A drift of debatable age, but apparently somewhat older than the Wisconsin drift, and referred provisionally to the Iowan stage of glaciation, extends a few miles beyond the undoubted Wisconsin drift in South Dakota, Minnesota, and Iowa and covers the Missouri-Mississippi divide nearly half way across Iowa. Its border passes under the Wisconsin near Wall Lake, Iowa. At the north it passes under the outer moraine of the Dakota, or James River, lobe near Florence, South Dakota. This drift is thinner than the Wisconsin and has an average thickness in its exposed portion of not more than 20 feet.

The next older drift is the Kansan, and this is found to have a thickness of 50 feet or more in places where least eroded, but its original thickness appears to have been less than 100 feet.

The Kansan and later drifts appear to embrace only 100 to 150 feet of the 300 to 700 feet of drift on the Coteau. The pre-Kansan drift thus has a much greater thickness than all the later drifts combined, the average thickness being not less than 250 feet and the greatest thickness over 500 feet.

Presented extemporaneously.

Discussed by W. M. Davis and J. B. Woodworth, with reply by the author.

DISCUSSION

Professor WOODWORTH called attention to Edward Hitchcock's recognition of glacial action and moraines in the Cape Cod region, published in an introductory (postscript) to his final report of 1841, evidently following in Agassiz's *Essai* of 1841.

WHAT CONSTITUTES THE ALTAMONT MORaine?

BY FRANK LEVERETT¹

(Abstract)

The Altamont moraine of the western limb of the Des Moines icelobe of the last, or Wisconsin, stage of glaciation was first noted by Prof. T. C. Chamberlin in 1878, and is described in his paper in the Third Annual Report of the U. S. Geological Survey (pages 378, 388, 393). He supposed it to be the outer moraine of the Des Moines lobe, and on the basis of this supposition the name Altamont has been applied to the outer moraine, both in the Des Moines lobe and in the Dakota, or James River, lobe to the west.

In the course of field-work in eastern South Dakota in 1912 the present writer found that the moraine on which the village of Altamont, South Dakota, stands is not the outer moraine of the Des Moines icelobe, there being a strong moraine outside which passes through Bemis, South Dakota. It was also found that it is this moraine, and not the one passing through Altamont, that has been mapped as the Altamont moraine in the reports of the Minnesota and Iowa Geological Surveys.

It was not until 1921 that the tracing of the moraine that passes through Altamont was carried around the loop in northern Iowa, in a joint survey by J. H. Lees, of the Iowa Geological Survey, and the present writer. The results of this survey and that of the present writer in Minnesota and South Dakota are set forth in figure 1. It is found that this morainic belt embraces the moraine south of Fort Dodge, Iowa, to which Dr. C. A. White called attention, under the name "Mineral Ridge," in 1870.² Doctor White suspected it to be a moraine, and interpreted it to mark a halt of the receding ice-border. He also recognized a later moraine in northern Iowa.

The outer moraine of the Des Moines lobe splits up into four weak members in northern Iowa, and these fade out into gently undulating ground moraine near the southern end of the lobe, in the vicinity of Des Moines, Iowa. The moraine which passes through Altamont does not show such weakness, but is a strong, well defined feature around the entire circuit of the morainic loop. On this account, as well as because it is the identical moraine to which Chamberlin applied the name Altamont, it seems advisable to let it carry the name and discontinue its application to the outer moraine. The writer proposes to apply the name Bemis to the outer moraine of the Des Moines lobe.

The course of the Altamont moraine in the Dakota, or James River, lobe has not been determined, so it can not now be stated whether it forms the outer moraine or, as in the Des Moines lobe, lies well within the border. The

¹ Published by permission of the Director of the United States Geological Survey.

² *Geology of Iowa*, vol. i, pp. 98-99.

shiftings of the ice movements were such that the outer moraine of one icelobe may not be the correlative of the outer moraine of a neighboring icelobe. For example, the outer moraine of the Green Bay icelobe is known to be older than the outer moraine of the Des Moines icelobe. So also the Shelbyville and Bloomington morainic systems of central and eastern Illinois are both older than the outer moraine of the Green Bay icelobe. From this it may be seen



FIGURE 1.—Map of the Des Moines Icelobe

that it is unsafe to carry correlations of moraines from one icelobe to another merely on the basis of numbering them first, second, third, etcetera. A continuous tracing of the moraines must be made. The Altamont moraine is likely to be of about the same age as the Port Huron morainic system of the Huron and Michigan basins and of Glacial Lake Whittlesey.

Presented extemporaneously.

Discussed by Morris M. Leighton, with reply by the author.

SECTIONAL MEETING OF WEDNESDAY AFTERNOON

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE AFTERNOON
SESSION AND DISCUSSIONS THEREON

The sectional meeting for the reading of stratigraphic papers convened in the afternoon, under the chairmanship of Vice-President Keith, while J. J. Galloway served as secretary. The following program was presented:

*VALUE OF THE PHYSICAL CHARACTERS OF SAND GRAINS IN THE
INTERPRETATION OF THE ORIGIN OF SANDSTONES*

BY J. J. GALLOWAY

(Abstract)

The study of sandstones may be approached from six different directions, namely, the physical characters of the grains, mineralogical character of the grains, structural features of the rock, paleontology of the rock, stratigraphic relations, and paleogeographic probabilities.

The physical characters of the grains include: (1) limits of size and average size; (2) proportion of different sizes (mechanical analysis); (3) percentages of angular, subangular, semiround, subround, and round grains; (4) proportions of rounding in the different minerals; (5) lower limit of rounding; (6) character of the surface of the grains; (7) coating on the surfaces of the grains.

Extensive experiments were conducted and observations made to determine the value of the physical characters of sand grains in the interpretation the agent of elastation, agent of transportation, and agent of deposition of sandstones. Limits of size and mechanical analysis were found to be of little value. When more than 50 per cent of the grains are well rounded, the sand is eolian, unless the sand is calcareous, in which case no agent of abrasion is indicated; if less than 50 per cent of the grains are well rounded, no agent of abrasion is indicated. If feldspars, garnet, zircon, mica, cassiterite, monzonite, or other minerals than quartz are rounded most, water abrasion and deposition is indicated. Grains of all common constituents of sands were rounded experimentally by mutual abrasion in water at velocities of four miles an hour or less to 0.01 millimeter in diameter; the lower effective limit of rounding by wind was found to be 0.03 millimeter, and the lower effective limit of rounding in water was found to be 0.05 millimeter in diameter. The presence, therefore, of a few round grains less than 0.1 millimeter in diameter in a sandstone is without significance. Wind-abraded grains of sand are "frosted" like ground glass; water-abraded grains are polished and glassy. A coating on grains indicates atmospheric weathering or abrasion in air at low velocities.

By a consideration of the mineralogical characters of sandstones, the structure of the grains (clastic or built up), the shape of the grains, and the surfaces of the grains, the agents involved in the formation and transportation of the materials of friable sandstones or sands can be accurately determined.

Read from manuscript.

Discussed by D. F. Higgins, who drew attention to the fact that lathe and planing-machine mechanics use water on the cutting edge to produce a polish on steel. Dry cutting gives a dull surface, often pitted.

RED LIMESTONES AND THEIR GEOLOGIC SIGNIFICANCE

BY J. J. GALLOWAY

(Abstract)

Red limestones occur in nearly every system from Cambrian to Quaternary, but their areal extent is usually small, and they constitute but a small percentage of the limestones of the geologic column. In the few cases which have been noted by geologists, the origin of red limestones and their geologic significance have not been discussed; or the unusual color is attributed to organic acids brought to the sea from the land during the deposition of the limestone, or to atmospheric oxidation due to oscillations of the sealevel during their deposition.

Many shades of red are represented: pink, scarlet, orange, brown, salmon, purple, maroon, and rose. Examples are: the Smith Point limestone (Lower Cambrian) of Newfoundland, bed 1*d* of the Weeks formation (Upper Cambrian) of Utah, the Manitou (Beekmantown) limestone of Colorado, the Holston marble (Middle Ordovician) of Tennessee, the Moccasin limestone (Black River) of Virginia, the Orthoceras limestone (Ordovician) of Sweden in part, the Brassfield limestone (basal Silurian) of Kentucky, the Chimney Hill limestone (Brassfield) of Oklahoma in part, the Percé beds of the Grand Greve limestones (early Oriskanian) of Gaspé, the Minnekahta limestone (Permian) of the Black Hills, the Chase limestone (Permian) of Oklahoma, the Dolores limestone (Permian) of Wyoming, the Halstatt limestone (Triassic) and Hierlatz limestone (Jurassic) of Austria, the Red Chalk (top of Lower Cretaceous) of England, the salmon-colored limestone (Miocene) of the Sierritas of Yucatan, the sepia-colored limestone (Pliocene and Quaternary) of northern Yucatan, and many brecciated marbles in America and Europe.

The color is due to limonite and hematite. Lithologically, red limestones vary from porous and chalky to dense and brittle, but are commonly earthy or nodular, massive and not well bedded, frequently brecciated by crushing, and are recemented. They are all fine grained except the crinoidal varieties. They are as fossiliferous as other kinds of limestone, and the fossils are partially replaced by lime or iron oxide and are frequently fragmental, worn, or crushed. Chemically, the limestones vary from nearly pure calcium carbonate, as the pink chalk of Yucatan, to very impure, with as much as 40 per cent of iron oxide, as the Red Chalk of England, and with much silica and clay, as the Manitou limestone. Organic matter other than calcium carbonate is absent.

Red limestones do not occur in beds of great horizontal extent, like ordinary limestones, but the outcrops only are red; they are not encountered in wells or tunnels except where a crushed zone is penetrated. They have long been exposed to weathering (most of the examples mentioned) or occupy unconformities where they have been subjected to weathering (Red Chalk and

Dolores), or have been crushed, weathered, and recemented (all commercial red or red mottled or streaked marbles and the Percé beds).

Red limestones are not known to be forming today, either in marine or fresh water, even where the conditions postulated for their original deposition exist, as along the coast of Florida and the north coast of Yucatan. Red limestones are now forming in Yucatan from the weathering and cementation of white chalk and limestone.

Red limestones were not originally red, but in all cases are due to atmospheric weathering. They always occupy present or past unconformities or crushed zones. They have no genetic relation to red beds of sandstone or shale. The porous examples are now being weathered, the iron oxidized, and the mass cemented by iron oxide and crystalline calcite. The dense examples have already passed through the porous stage and have been cemented in weathering. Limestones which do not become red on weathering are either dense, lack iron compounds, or contain carbonaceous organic matter, or are removed by erosion as fast as oxidation proceeds.

Read from manuscript.

Discussed by I. C. White, G. H. Chadwick, T. W. Stanton, and R. S. Bessler, with reply by the author.

DISCUSSION

Dr. WHITE: My observations agree perfectly with those of Dr. Galloway as to the origin of the red color and iron in limestones, namely, that in all cases it is the result of weathering or secondary causes. In the early eighties my studies of the Clinton fossil iron area in Montour, Columbia, and Huntingdon counties of Pennsylvania developed the fact that as we pass down below local drainage, level 200 feet to 300 feet, the iron area disappears into a reddish fossiliferous limestone, with only 8 to 10 per cent of iron remaining, and the inclosing shales, both above and below, retain their natural unleached color, instead of being white and leached, as they are where ore accumulation has taken place, their iron content having passed through weathering agencies from the shales to the cellular, honey-combed condition of the fossiliferous limestone matrix. It is my opinion that the thick Clinton iron ores of Alabama have had the same secondary origin source in all cases where iron ore occurs, the inclosing ferriferous shales having been leached and decolorized even at depths of 1,200 feet or more. However, in one deep boring no accumulation of ore was found, and there the inclosing shales were not decolorized, their iron remaining disseminated, and hence no leaching and no ore accumulation. Most geologists regard the Clinton iron ore of Alabama as an original deposition as ore, but your speaker thinks these ore deposits are the results of weathering or of secondary causes.

Professor CHADWICK: In the Rochester region the Clinton (Furnaceville) iron ore seems to represent a case of weathering of a fossiliferous limestone with replacement by iron before deposition of the overlying Reynales limestone; in short, a brief hiatus or disaster.

Mr. STANTON: The Manitou limestone, which was cited as an example of red limestone, is chiefly a gray limestone, as developed in Williams Canyon,

at Manitou, Colorado. The dark brownish red limestone of that section is a thin bed at the base of the Manitou, resting on the brown siliceous rocks of the Tawatch sandstone or quartzite. It has been somewhat doubtful whether this red limestone bed should be assigned to the Manitou or to the Tawatch. Its upper surface is somewhat irregular, suggesting that it was followed by an erosion interval which would give time for the weathering regional by Dr. Galloway's explanation of the origin and limestone. Under this conception, the red limestone bed in question belongs to the Tawatch cycle of sedimentation rather than to the Manitou.

Dr. BASSLER: In the discussion of the Clinton iron ore, I called attention to the fact that the thickest beds of such ore in the Appalachian district are in areas where the underlying red beds of Upper Ordovician age are either very thin or are entirely eroded away, thus seeming to indicate the sedimentary origin of the ore from preceding deposits.

PETROGRAPHIC STUDIES OF SOME NEW YORK SEDIMENTS

BY HAROLD L. ALLING

(Abstract)

The purpose of this paper, written for the stratigraphic paleontologist, is to call attention to the confirmatory and supplementary aid the petrographic microscope can furnish to students of normal sedimentary rocks. The instrument is of value in determining the conditions of deposition and manner of accumulation of clastic materials, thereby supplying information for the paleogeographer in his attempts to reconstruct the shorelines of ancient seas. The geologist working with highly metamorphosed sediments needs more information regarding normal sediments than is now available.

No difficulty is experienced with the terms "limestone" and "sandstone," but the meaning of the word "shale" is very indefinite. It seems best to assign a compositional significance to these common terms. Under this scheme many field determinations are subject to modification. For example, the Rochester "shale" at Rochester is an argillaceous dolomite; the Camillus "shale" is a waterlime. The composition of forty New York sediments is shown by diagrams which emphasize the insufficiencies of our present nomenclature. Examples are given where identification of formational units has been made by microscopic means alone, these tests being confirmed by paleontological evidence.

The microscope focuses our attention on the dual character of sediments—the cement and the mineral substances held together by the cement. A nomenclature is suggested which would be indicative of the dual nature of the composition of sedimentary rocks as revealed by the petrographic microscope.

Read from manuscript.

LIFE ERAS BEFORE THE CAMBRIAN

BY CHARLES R. KEYES

(Abstract)

Recent astonishing lowering of the life record into the abyss of time, as at Steep Rock Lake, in Ontario, and in the Canadian and Montana Rockies, does

not necessarily support the claim, so often made, that since at the beginning of Cambrian time life was already nine-tenths differentiated; biotic development spans an interval ten times as long as that which has elapsed since that date to the present day. In organic expansion there are grave crises wherein growth and change are accelerated more in brief episodes than those which take place in the millions of years which lie between. The intellectual development which took place since mid-Tertiary times and the rapid structural changes which transpired when the land fauna was established are well known. An earlier and more important crisis was, as Brooks points out, the discovery by life of the bottom of the sea. Bearing this feature in mind, the inferential immensity of the pre-Cambrian time-span is immeasurably cut down. Before the Proterozoic and Archeozoic eras, there was, perhaps, a single other Eozoic era of which we do not yet take definite cognizance, of equal length, before reaching the Azoic chaos. According to the best revised estimates, therefore, 500,000,000 years have elapsed since life on our planet was originally initiated or created.

Presented by title in the absence of the author.

*QUANTITATIVE STUDY OF THE DERIVATION OF NORTH AMERICAN
ALGONKIAN SEDIMENTS*

BY ARTHUR C. TROWBRIDGE AND WALDO S. GLOCK

(Abstract)

An attempt to test quantitatively the usual statement that North American Algonkian sediments were derived from the erosion of North American Algonkian lands underlain by Archean rocks results in the conclusion that about 11,000,000 square kilometers of land surface must have been degraded to an average depth of about 8,400 meters, to account for the free quartz found in Algonkian sediments. The paper describes the methods used, under several different assumptions of depositional and erosional areas, etcetera, in arriving at this general conclusion. The results of the estimates are discussed in terms of plural erosional cycles and the duration of Algonkian times.

Presented by title in the absence of the authors.

CAMBRO-ORDOVICIAN SECTION NEAR MOUNT ROBSON, WESTERN CANADA

BY LANCASTER D. BURLING

(Abstract)

The Cambrian and Ordovician of the Mount Robson region have been described as comprising the following eleven formations: Robson (Ordovician); Lynx (Upper Cambrian); Titkana, Mumm, Hitka, Tatay, and Chetang (Middle Cambrian); and Hota, Mahto, Tah, and McNaughton (Lower Cambrian).

Detailed sections prove that the mountains adjacent to Mount Robson expose strata differing from those which the earlier reports would lead us to suppose. The more important of the necessary corrections are: (a) Mount Robson, described as exposing in its summit 3,000 feet of Robson limestones above the

Extinguisher ("Billings Butte") fauna, is probably capped by the Extinguisher fauna; (b) Mount Rearguard ("Iyatunga"), stated to contain a well exposed section of the Titkana, exposes in its place a fine section of the Lynx; and (c) Mount Mumm, the type locality for the "Mumm" formation, contains neither the "Mumm" nor its equivalent (the Tatei), but does expose, in the described position for the "Mumm," the "Hota" and the lower portion of the Chetang.

Evidence is presented for a number of other discoveries, the more important of which are: (a) the stratigraphic position of the hitherto unplaced Extinguisher fauna; (b) the contact between the Upper Cambrian and the Ordovician; (c) the upper half of the Lynx formation; (d) the identity of the Titkana and the "Hitka"; (e) the identity of the Tatei ("Tatay") and the "Mumm"; (f) the bewildering confusion, in the field and in the published reports, of the Mumm, Hota, and Tah limestone formations; (g) the Middle Cambrian age of the "Hota," for which the term Adolphus is proposed; and (h) the fact that it is the "Tah" limestone, for which the term Mural limestone is proposed, and not the Hota or the Mahto, which is the source of the drift blocks carrying the new Lower Cambrian subfauna described by Walcott and the *Pædumias* described by the writer.

General fossil collections have previously been recorded and described from three only of the eleven formations listed in the first paragraph. The new conclusions are based on a very brief reconnaissance, but their accuracy is attested by collections from numerous fossil horizons in all but the two basal quartzites of the nine formations now known to occur in the district, as follows: Unnamed Ordovician (Robson?); Lynx (Upper Cambrian); Titkana, Tatei, Chetang, and Adolphus (Middle Cambrian); Mahto, Mural limestone, and an unnamed underlying quartzite series (Lower Cambrian).

Presented by title in the absence of the author.

TRENTON OF CENTRAL TENNESSEE AND KENTUCKY

BY PERCY E. RAYMOND

(Abstract)

The strata of Trenton age in Kentucky have been carefully studied by Doctors A. M. Miller and A. F. Foerste and afford a standard with which to compare the somewhat less known series in the Nashville dome. Physical conditions differed in the two regions during the deposition of the rocks, so that a satisfactory correlation of the various subdivisions can only be reached through a careful study of the history of sedimentation in both. This history appears to explain the migrations of a "recurrent fauna," and the correlation reached varies in some respects from that generally accepted.

Presented extemporaneously.

Remarks were made by R. S. Bassler and E. O. Ulrich, with reply by the author.

STRATIGRAPHY OF THE CRYSTALLINE SCHISTS OF PENNSYLVANIA AND MARYLAND

BY ELEANOR BLISS KNOFF AND ANNA I. JONAS

(Abstract)

This paper presents the results of field studies in the crystalline schists of southeastern Pennsylvania and Maryland. The crystalline schists of Baltimore County, Maryland, are Precambrian. The base of the section is the Baltimore gneiss, a highly crystalloblastic paragneiss injected in some places by granitic magma. Overlying the Baltimore gneiss is the Glenarm series of recrystallized sediments, whose thickness is provisionally estimated at 8,000 to 10,000 feet. These rocks show a metamorphism whose intensity decreases progressively from highly crystalline schists at the base to mildly anamorphosed sediments at the top. The lower formations of the Glenarm series are cut by plutonic intrusions, and the upper formations contain amphibolite schists that are probably metamorphosed volcanics and may be the equivalent of the Precambrian Catoctin lavas.

The Precambrian core of the Reading-Durham Hills in Pennsylvania is a completely recrystallized paragneiss injected by various plutonic rocks. The cover of Paleozoic sediments is very slightly altered. In Mine Ridge Hill, which is the western termination of the upland that lies on the northwest side of Chester Valley, the Precambrian core is lithologically similar to the rocks of the Reading Hills. The sedimentary series on the flanks of Mine Ridge Hill is thoroughly crystalline, but is considered to be Paleozoic and to represent the metamorphosed equivalent of the Lower Cambrian arenaceous sediments in the Hellam-Chickies ridge, northwest of Mine Ridge Hill.

The intensity of metamorphism in the region does not die out gradually from southeast to northwest across the strike of the folds, but there are three belts of intense metamorphism that lie parallel to the folds in northern Maryland and southern Pennsylvania, and these belts are separated by areas of diminished metamorphic intensity. There is also a waning of metamorphic intensity from the lowest to the uppermost Precambrian formation, succeeded by a renewed intensity in the Paleozoic rocks of Mine Ridge Hill.

Therefore the metamorphism can not be explained as a result of simple dynamic action where the intensity is conditioned by distance from the locus of initial yielding to the folding force, nor as simple load metamorphism conditioned by depth of burial. A combination of load metamorphism and regional contact metamorphism is a possible explanation of the localization of areas of intense metamorphism. Further stratigraphic work will be necessary, however, before any theory of metamorphism for the region can be proved.

Read from manuscript by the senior author.

Discussed by Florence Bascom and G. H. Ashley.

DISCUSSION

Professor BASCOM stated that she could not let the paper pass without commenting on what must be evident to the Society, the value of the kind of detailed and elaborate study which the paper represented. The Piedmont has

been no happy hunting ground for geologists. It offers no spectacular geology, no economic interests of striking importance, but all the principles of metamorphism are exemplified within it; variable metamorphism and deep-seated erosion confuse and conceal the stratigraphy. It is only by such elaborate study of wide areas that the geology of the Piedmont can be worked out.

Dr. ASHLEY: Some further idea of the difficulty of the problems may be gained if we recall that Lancaster County, in this field, is reported to be the richest agricultural county in the United States, and Chester County is said to come next. This means a lack of rock outcrops that render satisfactory work almost impossible.

PROPOSED NEW NOMENCLATURE OF THE APPALACHIAN COAL MEASURES

BY GEORGE H. ASHLEY

(Abstract)

Attention is called in the paper to the conditions existing in the naming of the beds of coal, sandstone, clay, shale, and limestone of the Appalachian "Coal Measures," and of the need of some improved method of naming which will cover the whole region. Recent work is cited and the proposal is made of a system consisting of the principal and most widely accepted "formation" names, combined with capital letters, to be applied to subdivisions of each formation of approximately 50 feet each. Thus: Allegheny E applies to any rock in "measures" or "member" "E" in the Allegheny formation. This member covers from the top of the Freeport Lower coal to the top of the Freeport Upper coal. Thus the Butler sandstone becomes the Allegheny E (Butler) sandstone (the old local name always being added in parentheses). The Alma coal of West Virginia becomes Kanawha L (Alma) coal. The Taggart coal of Virginia also becomes Kanawha L (Taggart) coal.

The paper presents a type section taken from the Pocohontas-New River-Kanawha-Pittsburgh areas, and suggests possible or probable correlations for the better known coals of other parts of the Appalachian coal region.

Read in abstract from manuscript.

Discussed by I. C. White, David White, and D. F. Higgins, with reply by the author.

DISCUSSION

Dr. I. C. WHITE: The new classification scheme of Dr. Ashley is so revolutionary that its general adoption will prove very difficult. Old names of coal beds, or those first given and used by the mining fraternity, tend to stick even when the correlation is erroneous; so that I fear that any new nomenclature will prove just as confusing and difficult of general adoption as that mentioned by Dr. Ashley in the case of the numbering of the coal beds in Indiana and Illinois, where neither State would change the numerical order of its coal beds to conform in correlation to those of the other State.

Mr. DAVID WHITE held the view that a classification such as that proposed seemed practicable only on the supposition that the correlations of the beds were final and not susceptible to changes.

Mr. HIGGINS: To name beds below the arbitrary zero bed would require but the prefix of a minus sign. Slight changes, from 49*g* to 49*c*, for example, are of no practical import to the engineer, for in estimating reserves he requires only a convenient scale.

Dr. ASHLEY, in reply, pointed out that his proposed nomenclature was primarily for adoption for a type section against which future work may be set.

*REVISION OF THE PALEOZOIC SYSTEMS, PART II: THE ORDOVICIAN
SYSTEM*

BY E. O. ULRICH

(*Abstract*)

The paper gives a definition of the Ordovician system as restricted in the first part, followed by more or less detailed notes on the formations and their correlations.

Read in abstract from manuscript.

Discussed by J. J. Galloway, G. H. Chadwick, A. F. Foerste, R. S. Bassler, and Arthur Keith, with reply by the author.

DISCUSSION

Dr. GALLOWAY: I wish to call attention to the unconformity above the Moccasin red limestone, the color of which is due to weathering during the unconformity.

Dr. FOERSTE: The paper by Dr. Ulrich is an excellent illustration of the limited geographical area occupied by some formations and of the frequency with which strata of similar lithological appearance in areas not far apart may belong to more or less distinct parts of epicontinental basins, may contain distinct faunas, and may belong to distinct horizons. It demonstrates the danger of identifying formations in new areas on the basis of relatively few fossils before their faunas are more fully known. Within relatively small areas it frequently is possible to demonstrate the presence of quite distinct basins of depositions. The Niagaran of Adams and Highland counties, in southern Ohio, for instance, is quite different from that in the more northern countries, Montgomery, Miami, and Darke. The latter, again, differ from the Niagaran of Indiana. And yet those very different areas of deposition lie within relatively short distances from each other.

The section adjourned at 5.20 o'clock p: m.

SESSION OF WEDNESDAY EVENING

PRESIDENTIAL ADDRESS AND SMOKER

At 8 o'clock Wednesday evening the address of the retiring President was delivered in College Hall. It is entitled

AFTER-EFFECTS OF IGNEOUS INTRUSION

PRESIDENTIAL ADDRESS BY JAMES F. KEMP

The address was delivered from manuscript. It is published as pages 231-254 in this number of the Bulletin. After the reading of President Kemp's address, the room was cleared and the annual subscription smoker of the Society and its three affiliated societies was held. The function was largely attended and very enjoyable.

SESSION OF THURSDAY, DECEMBER 29

The Society convened at 9.35 o'clock, with President Kemp in the chair. After announcements by the Secretary, the Auditors made the following report:

REPORT OF THE AUDITING COMMITTEE

The Auditing Committee has examined the accounts of the Treasurer for the year 1921 and finds them correct as set forth in the statement.

Very respectfully,

HARRY FIELDING REID,

EDSON S. BASTIN,

DECEMBER 29, 1921.

Committee.

After accepting the report of the Auditing Committee the Society took up the annual report of the Council, which had been received from the printers in the early mail and had been distributed, and accepted it.

SYMPOSIUM ON ISOSTASY

The Society then proceeded to the consideration of the symposium on isostasy, which was introduced by the following papers:

THEORY OF ISOSTASY—A GEOLOGICAL PROBLEM

BY WILLIAM BOWIE

This paper was presented extemporaneously.

*CONDITION OF THE EARTH'S CRUST AND THE EARLIER AMERICAN GRAVITY DETERMINATIONS*BY GEORGE R. PUTNAM¹

Read by T. Wayland Vaughan in the absence of the author.

¹ Introduced by William Bowie.

*SOME CONSIDERATIONS TOUCHING ON ISOSTASY*BY H. O. WOOD¹

Presented by title in the absence of the author.

ISOSTASY AND EARTH MOVEMENTS

BY HARRY FIELDING REID

Presented extemporaneously.

ISOSTASY AND APPLIED GEOLOGY

BY JAMES F. KEMP

Read from manuscript.

*FOLDING OF MOUNTAIN RANGES—THE ARGUMENT FROM ISOSTASY*BY SIR SIDNEY BURRARD¹

Read by W. Bowie in the absence of the author.

ISOSTATIC COMPENSATION CONSIDERED AS A CAUSE OF THRUSTING

BY ANDREW C. LAWSON

Presented in abstract extemporaneously by Harry Fielding Reid in the absence of the author.

ISOSTASY AND ROCK DENSITY

BY HENRY S. WASHINGTON

Presented extemporaneously.

WEIGHT OF SEDIMENTS PER UNIT VOLUME

BY ALFRED C. LANE

Presented extemporaneously.

ROLE OF ISOSTATIC STRESS

BY BAILEY WILLIS

Presented by title in the absence of the author.

The following members took part in the discussion: A. C. Lane, William Bowie, W. M. Davis, H. F. Reid, H. S. Washington, F. D. Adams, Charles Schuchert, D. F. Higgins, L. C. Graton, Frank Leverett, David White, and H. F. Cleland.

¹ Introduced by William Bowie.

The papers composing the symposium will be printed in full in this volume of the Bulletin.

The Society adjourned about 12.30 p. m. for lunch.

SESSION OF THURSDAY AFTERNOON

On reassembling in the afternoon the Society met in two sections. The first, under the chairmanship of Vice-President Woodworth and the secretaryship of Douglas W. Johnson, listened to the following papers:

TITLES AND ABSTRACTS OF PAPERS PRESENTED AT THE AFTERNOON
SESSION AND DISCUSSIONS THEREON

COMPARATIVE STUDY OF THE NEBRASKAN AND KANSAN TILLS IN IOWA

BY GEORGE F. KAY

(Abstract)

The prevalent opinion among Pleistocene geologists has been that Nebraskan till can be distinguished without difficulty from Kansan till by differences in physical characters of these two tills. Recent detailed investigations of Nebraskan and Kansan tills, where the evidence admits of no doubt as to their correct identification, has shown conclusively that this view must be modified. Many excellent exposures of these two tills, separated by materials which could have been formed only during an interglacial epoch of long duration, have been made available for study in recent years in connection with railway construction and the improvement of the roads of the State. The evidence gained from a study of these exposures in widely distributed areas in Iowa justifies the conclusion that, whereas it is true that in some parts of Iowa the Nebraskan and Kansan tills can be distinguished by their differences in color, texture, structure, lithologic composition, and related features, as was pointed out by Carman in his report on the Pleistocene history of northwestern Iowa, nevertheless there are many areas in Iowa within which these two tills resemble each other so closely that it is impossible to determine by physical characters whether a particular outcrop of till is Nebraskan till or Kansan till. In such places the only satisfactory basis thus far found in Iowa by which it is possible to decide whether the till is Nebraskan till or Kansan till is the relationship of the till to interglacial material the age of which can be determined. Among the most widespread and most significant of these interglacial materials is gumbotil. If a till is overlain by Nebraskan gumbotil or can be shown to be related to Nebraskan gumbotil, which in Iowa is found as remnants of a former extensive Nebraskan gumbotil plain, the till is Nebraskan till. If, however, the till is overlain by Kansan gumbotil or can be shown to be related to Kansan gumbotil, which also is found as remnants of a former extensive Kansan gumbotil plain, the till is Kansan till.

Presented in abstract extemporaneously, with lantern-slide illustrations.

Discussed by M. M. Leighton and W. M. Davis.

*FURTHER DATA ON THE DIFFERENTIATION OF THE GLACIAL DRIFT SHEETS
OF NORTHERN ILLINOIS*

BY MORRIS M. LEIGHTON

(Abstract)

The work of the past season has yielded additional evidence which verifies the conclusions of the previous season, as presented at the Chicago meeting of the Geological Society of America, that the glacial drift west of the outer Wisconsin moraine must be differentiated into two distinct sheets—one of Illinoisan age, which extends to the border of the Driftless Area, and the other, apparently of Early Wisconsin age, which overlies the Illinoisan and extends as far west as Stillman Valley, in Ogle County. The limits of the younger drift have been determined, and because of its lobate form and its typical development immediately south of Belvidere it is referred to as the Belvidere lobe.

South of Dixon, in territory far beyond the Bloomington moraine, and which at one time was mapped as Iowan, and later as Illinoisan, relatively fresh drift was found bearing the same definite aspects of youth and the same relations to the Illinoisan as the Belvidere lobe. Some evidence was also found suggesting that the strip of drift on the south side of the Green River basin, between Sheffield and Geneseo, is also of the same age, which, if true, indicates that a lobe of Early Wisconsin ice invaded the Green River basin as far west as Rock River. It is hoped that a short additional period of work will definitely clear up this remaining question as to the drift of northwestern Illinois.

Presented in full extemporaneously.

Discussed by Frank Leverett, J. W. Goldthwait, and W. M. Davis, with response by the author.

DISCUSSION

MR. LEVERETT: The boundary drawn by Professor Leighton does not seem to be in accord with the observations made some years ago by Leverett of the extent of a drift that is separated from the underlying Illinoisan drift by fossiliferous silts and by a fresher aspect. The extent of this overlying drift is set forth in Monograph XXXVIII, U. S. Geological Survey, under the name "Iowan drift." The leaching tests presented by Leighton seem less conclusive than supposed by him, for texture and other features need to be considered.

PROFESSOR LEIGHTON (in reply): I appreciate the criticisms of Mr. Leverett. In regard to the exposure at Polo, I may say that the cut is now obscured by slump and sod, but an attempt to reexpose the materials resulted in finding only one till, and another worker had previously failed to identify the two tills and an intervening loess with an auger, although they may be there. At Polo a gumbotil lies at the top of the till, the like of which is not known for the Belvidere area. The calcareous portion of the loess of this area also rests

on leached till, whereas in the Belvidere area, where the auger penetrated till beneath calcareous loess, the till was calcareous. In places a soil zone separates the loess and underlying till in the area which I have mapped as Illinoisan, but not in the Belvidere lobe; likewise an old loess, like clay, separates the relatively fresh loess from the underlying till in the former area, but not in the latter. These stratigraphic relations of loess and till seem to me to be fundamentally important in distinguishing the two areas. The boundary between the two areas is different from that appearing in Monograph XXXVIII. As for the average depth of leaching which I cited, the depths found do not have a uniform range from 0 to 8 feet, giving an average of 4, but the great majority are around 4 feet. This will be brought out in my more detailed report, but the average depth was emphasized for me—the process of field-work by the fact that calcareous till in the Belvidere lobe was encountered either just at the depth of the first auger section of $3\frac{3}{4}$ feet or just after adding the second section.

LATE PLEISTOCENE HISTORY OF THE LOWER MOHAWK AND MIDDLE HUDSON REGION

BY JAMES H. STOLLER

(Abstract)

Some additional data gathered in recent field-work seem to afford a clear explanation of the drainage history of the region, concerning certain features of which divergent views have previously been held, and also have a bearing on the more general problems of the Pleistocene history of the Hudson-Champlain Valley. The key to the drainage history and the resulting physiographic features is found in the repeated shifting of the course of the Iroquois-Mohawk River, as its flooded and sediment-bearing waters flowed across an area from which the static waters of the Mohawk-Hudson region were receding. The origin of Saratoga Lake and of Round Lake, of the "old channel of the Hudson west of Schuylerville," of the inlet of the Hudson River at Coveville, and of other features, is considered.

Presented by title in the absence of the author.

ABLATION OF THE EASTERN LOBE OF THE WISCONSIN ICE-SHEET

BY JOHN H. COOK¹

(Abstract)

By the term "eastern lobe" is designated all that body of glacial ice forced southward beyond the mountain barriers of northern New York, Vermont, New Hampshire, and Maine and lying east of the lobe which spread south and southeast from the Ontario basin. Within this area the influence of larger and smaller masses of stagnant ice in shaping the existing topography has been widely recognized and the evidences of continued movement of the lobe during the period of "recession" have been found to be meager. The frontal

¹ Introduced by John M. Clarke.

recessional moraines are commonly short, detached sections which can not be correlated along continuous ice-front positions. Some of these drift accumulations are open to an interpretation other than that of frontal moraine. This absence of effects is in strong contrast to the topography produced by the gradual shrinkage of a field of "live" ice.

In the eastern headwaters of the Susquehanna basin and in the Hudson Valley and some of its tributary valleys, long tongues and wide areas of stagnant ice can be shown to have outlasted the glacio-natant streams and to have existed in part contemporaneously. From the Helderberg escarpment northward to Glens Falls remnants of a stagnant field outlived the deep-water flooding of the Champlain-Hudson Valley.

It is held (1) that the friction of the mountain barrier, the loss of grade due to the subsidence of the crust under the central portion of the Labrador ice-field, and the flotation of the glacier by the sea in the Saint Lawrence Valley cooperated to deprive the eastern lobe of the pressure necessary to keep it in motion; (2) that this part of the glacier stagnated early in the period of recession; (3) that much of the topography of southern New England, New York, and northern New Jersey can be best interpreted as due to thick glacial ice melting *in situ*; and (4) that such phenomena as the late movement of the ice from the Hudson Valley westward up the valley of the Mohawk are best explained as the result of live ice moving into the stagnant field and finding avenues of pressure relief other than overthrusting on the dead ice.

Read from manuscript.

*PRELIMINARY NOTES ON THE SHORELINES OF GLACIAL LAKE NASHUA,
NEAR FITCHBURG, MASSACHUSETTS*

BY THOMAS C. BROWN

(Abstract)

This paper described briefly some of the shorelines as they occur in the vicinity of Fitchburg, Lurrenburg, and Townsend.

Presented without notes.

*MAP OF THE PLEISTOCENE LAKES OF THE BASIN-AND-RANGE PROVINCE
AND ITS SIGNIFICANCE*

BY OSCAR E. MEINZER

(Abstract)

This brief paper reviews the work that has been done in discovering and mapping the Pleistocene lake beds of the Basin-and-Range province, presents a map showing the 67 known Pleistocene lakes in the province, and suggests a method of comparing the Pleistocene and present hydrology and climate of the region.

Read in full from manuscript, with lantern-slide illustration.

Discussed by W. M. Davis.

DISCUSSION

Professor DAVIS: I am much gratified to learn that the National Survey proposed to take up again the study of the many intermont basins and extinct lakes of the Great Basin, and desired to make a brief historical statement in that connection.

The younger members of our Society may not recall that 42 years ago, in 1879, when the several departmental geological surveys of the period of early western exploration were abolished and the United States Geological Survey was created to unify and replace them, G. K. Gilbert was one of six members of the earlier surveys to be appointed as "geologist" in the new organization; and that its first director, Clarence King, gave Gilbert charge of the Great Basin division of the Survey, with headquarters at Salt Lake City, where he was to continue the studies he had previously begun on the extinct Lake Bonneville, with the expectation that the study of other extinct lakes in the same region would be taken up later.

When King resigned, in 1881, and Powell was made Director, Gilbert was called to Washington, there "to complete his report on Lake Bonneville," while his assistants were to continue the study of other Great Basin lakes. In 1884 he reported that, besides Bonneville, which he and his assistants had studied, and Lahontan and Mono, which had been studied chiefly by Russell under his direction, 25 of the smaller extinct lakes had been explored, but that a still larger number probably remained to be examined. It was, however, only the three larger lakes above named which were specially reported on; studies of the smaller ones were stopped.

Russell and other western-trained geologists were called to the East and assigned to Appalachian studies under Gilbert's direction. Gilbert's completion of his Bonneville report was long delayed by his work on various other tasks, and "the examination of the more southerly valleys [of the Great Basin], . . . the study of the brines and the saline deposits, and the elaborate measurement of post-Pleistocene displacements," all of which he had hoped to see accomplished, were indefinitely postponed.

So many were the distractions by which the Bonneville monograph was delayed that it was not published until 1890, nearly ten years after Gilbert had been recalled from Salt Lake City to complete it. It is numbered Monograph I, as if it were to have been the first to be issued; but 15 others, including Russell's monograph on Lahontan, appeared before it. There can be no question that Gilbert deeply regretted the necessity of transferring his attention from research in the West to a variety of other duties in the East; he was in particular disappointed to have to give up his studies on the deformation of the Bonneville basin, apparently due to the evaporation of the lake waters; for he was there approaching a quantitative determination of a problem concerning the balanced condition of the earth's crust which has later been given the name of isostasy.

In December, 1885, in his famous address as president of the Society of American Naturalists, he examined this aspect of the Bonneville problem under the title of "The inculcation of scientific method by example," and he then said: "It is hardly necessary to assure you that my personal regret in abandoning this research at its present stage is very great." That brief state-

ment is really an epitaph over a buried investigation, the epitaph over a child by its parent. In spite of his disappointment, he most loyally devoted himself to the duties which Powell asked him to undertake, but he permitted himself an expression of feeling in an annual report to his Director: "While I recognize fully the considerations which led to the closing of this investigation of the Great Basin, and while the wisdom of your decision is unquestioned, I yet find myself unable to lay the work aside without the tribute of regret and the expression of a hope that it may some day be resumed by another if not by myself."

Gilbert never had opportunity of returning to his Pleistocene studies in the West; but those of us who looked with admiration on what he did accomplish and who looked with affection to him must rejoice that, if his wish to resume the studies himself could not be gratified, his alternative wish, that they should be resumed by another, is now about to be realized.

*IS THE CHANNEL OF THE MISSOURI RIVER THROUGH NORTH DAKOTA OF
TERTIARY ORIGIN?*

BY JAMES E. TODD

(*Abstract*)

A few years ago the State Geologist of North Dakota published his conclusion that the course of the Missouri was determined in Tertiary time and was strictly preglacial. His reasons may be briefly stated as follows: (1) No channels in that State have been found to run across the present course of the Missouri toward the north and east. (2) Glacial boulders have been found 125 feet below the surface of a low terrace along the Missouri River near Bismarck. (3) Glacial gravel has been found capping a terrace 55 or 60 feet above the Missouri River, between Mandan and the mouth of Knife River. (4) Between Sawyer and Price this terrace is capped with till 30 to 40 feet thick. (5) A little below the mouth of Tobacco Garden Creek, on the north side of the Missouri, is a mass of glacial boulders 12 feet or more in thickness, which extends for a hundred yards along the river.

To the first point it may be replied that he is evidently looking at too low an altitude, and that it is possible for channels to be very thoroughly hidden by a deposition of till. The valley of the Yellowstone, though just beyond the west line of the State, has been traced over the divide to the Souris River, and the valley of Long Lake may be readily shown to be possibly the preglacial channel of the Cannon Ball River. The second point loses its value if we remember the depth to which flooded streams may scour their channels. When we remember the abundant water of Apple Creek, derived from the ice-sheet a few miles farther east, it is not difficult to suppose that these large boulders found their place on bedrock in the latter part of the Glacial period. Third, the position of glacial gravel and boulders on the terrace above Mandan may be similarly explained. Fourth, the occurrence of many feet of till on the terrace is a good argument for supposing that the terrace was there when the glacier passed over it; for till is admitted to be a subglacial deposit. But it may have been the valley of Knife River rather than the valley of the Missouri. Fifth, the unusual deposit of boulders near Tobacco Garden Creek has

little significance; for, where boulders are abundant, boulder bars may form in vigorous streams adjacent at any time.

Considering these points alone, we must claim that it has not been proven that the valley of the Missouri is preglacial.

Presented by title in the absence of the author.

FORMER COURSES OF THE ANDROSCOGGIN RIVER

BY IRVING B. CROSBY¹

(Abstract)

The present course of the Androscoggin is largely preglacial in origin, being composed of parts of three preglacial drainage systems. The upper part of the Androscoggin drainage basin was formerly tributary to the Connecticut River. The middle part drained through the basin now occupied by Sebago Lake into the ocean south of Portland, and the drainage of the lower part was somewhat as at present. The disarrangement of drainage lines in the middle and lower parts was due to heavy deposits of glacial drift. The upper part was captured from the Connecticut system by preglacial piracy.

Presented by title in the absence of the author.

PENEPLAINS AND THE GEOGRAPHIC CYCLE

BY WILLIAM MORRIS DAVIS

The full paper is to be published in this volume of the Bulletin.

Presented in abstract extemporaneously.

Discussed by D. W. Johnson, Oscar E. Meinzer, and H. F. Cleland.

DISCUSSION

Professor JOHNSON: It is desirable to distinguish between the uplifted deposit of sediments commonly called a coastal *plain* and a level surface of erosion bordering the coast, which is sometimes also called a coastal plain. By employing the spelling *plane* for planes of erosion, the desired distinction will at least be apparent on the printed page and the confusion evident in some reports be avoided. A *peneplane* is almost a plane surface of erosion, a region *planed* down by the agents of erosion. The spelling *ane* instead of *ain* has proved useful to the speaker, while at the same time being closer to the Latin root and less open to criticism as a hybrid.

RETROGRADING OF OFFSHORE BARS

BY DOUGLAS W. JOHNSON

(Abstract)

In the normal development of a shoreline of emergence there occurs a stage during which the offshore bar retreats landward under the continued attack of the waves. Inasmuch as this process of retrograding involves the super-

¹ Introduced by W. O. Crosby.

position of the sand or gravel of the bar on the marsh or lagoon deposits formed back of the bar, it has usually been assumed that a typical cross-section of the shore formations at this stage must show peat, silt, or similar material immediately beneath the retreating bar. Absence of such material might accordingly be interpreted as indicating no retrogression of the bar. The paper shows that frequently marsh and lagoon deposits are not present beneath a retreating bar; that the presence of such materials in notable quantities should be expected only as an exceptional feature, and that normally they will be present in very small quantities or wholly absent.

Presented in abstract extemporaneously, with lantern-slide illustration.

ROLE OF CROSS-WAVES IN THE FORMATION OF TOMBOLOES AND POINTS

BY ROSWELL H. JOHNSON

(Abstract)

A wave meeting an island off a shore at not too great a distance has its course bent because of the gradient of bottom out from the island in every direction. The result is to cause the beach directly back of the island to receive waves at two different opposed angles. These may be called cross-waves. Photographs of such cross-waves with the sandy point which they produced will be shown. This would eventually be built up into a tombolo within certain limiting conditions.

Theoretically, a shoal with sufficiently sharp gradients on a shore where the prevailing wind does not show too great an angle with the shore should also act in this way and produce a looped bar or a pointed sandy prolongation to leeward and a sandy point of the shore, if not too distant.

The data are considered worth presenting, as the literature stresses so much the opposite movement from forelands to bay-heads; also as another way in which thick deposits of sand can be formed where not subject to reworking, in the case of a transgressing sea.

Presented extemporaneously, with lantern-slide illustration.

Discussed by Douglas W. Johnson.

DISCUSSION

Professor JOHNSON: The speaker expressed the opinion that the essential factor in forming the cusped forelands described by Mr. R. H. Johnson was the longshore action of wave-currents causing beach drifting from opposite directions toward a common point, and that the cross-waves were incidental to the process rather than causal. He showed that the same result is produced back of an island without the formation of cross-waves, when shifting winds drive waves in first from one direction, then from another.

GEOLOGY OF THE COLORADO RIVER IN SOUTHEASTERN UTAH

BY C. R. LONGWELL, H. D. MISER, R. C. MOORE, AND SIDNEY PAIGE

(Abstract)

Geologists of the U. S. Geological Survey, working along Colorado and San Juan rivers in the summer of 1921, studied many detailed stratigraphic sec-

tions representing a large area. The oldest formation seen was the Goodridge, of Pennsylvanian age. Shales overlying the Goodridge formation along San Juan River are believed to correspond to the Hermit shale of the Grand Canyon section. These shales are in turn overlain by cross-bedded sandstone, at least 1,000 feet thick, which forms the walls of Cataract Canyon on Colorado River. Apparently this sandstone, which is overlain unconformably by the Moenkopie formation, occupies the place of the Coconino sandstone and the Kaibab limestone of the Grand Canyon section. The Moenkopie formation thins and becomes sandy toward the north. The De Chelly sandstone is evidently an irregular lentil wedging into the Moenkopie. The Shinarump conglomerate, with all its characteristic features, is present in the area, but it becomes discontinuous toward the north. Many features of the Chinle and La Plata formations were noted for comparison with sections in other areas. Structural and physiographic features were also studied.

Presented in full by C. R. Longwell without notes, with lantern-slide illustration.

Remarks were made by W. M. Davis and David White.

DISCUSSION

MR. DAVID WHITE: It is appropriate here to call attention to the correlations recently made of the De Chelly with the Coconino by Mr. Darrey Hogu in a very recently published paper on "Oil possibilities of the Holbrook area in Arizona." In autographically corrected copies received from Mr. Hogu, the former correlation by him of the La Plata with the De Chelly is rescinded and the De Chelly is made equivalent to the Coconino, the upper Goodridge of the San Juan area being attached to the Supai. The Moenkopie of Woodruff and Gregory, in the San Juan region, he places with the Supai. This record is submitted at Mr. Hogu's request.

CAMBRIAN SUCCESSION OF NORTHWESTERN VERMONT

BY ARTHUR KEITH

(Abstract)

The Champlain Valley, in northwestern Vermont, afforded for years the type section of the Lower Cambrian, and the town of Georgia gave its name to the series. This series, or group, is divided in this paper into ten formations of quartzite, dolomite, limestone, and marble. Four formations of later Cambrian and eight of Ordovician age are also recognized, including sandstone, dolomite, limestone, marble, and slate. Numerous new localities for fossils are described. The term Georgia is shown to have no longer a large taxonomic value.

Conglomerates, mainly basal, are described at six horizons; three of them are of major importance and follow long erosion intervals. Two great overlaps are recorded. The formations fall into three groups or sequences, formed under different environments, and now crowded into contact by great overthrusts. One great deformation took place in the late Precambrian and was followed

by the Lower Cambrian overlap. Later deformation seems to have taken place in the Middle Cambrian and to have been followed by an Upper Cambrian (Saratogan) overlap. The principal deformation is of the usual Appalachian kind.

Presented in full extemporaneously.

Discussed by C. E. Gordon, with reply by the author.

DISCUSSION

Professor GORDON : I was very much interested in Mr. Keith's paper. My own studies in Vermont geology have carried me into the northwestern part of the State, where I have observed and traced, throughout their extent, the boundaries of the great thrust displacements which are depicted on Mr. Keith's map. After recognition of the general age relations of the rocks involved, these great thrust displacements are hardly less clearly visible in the field than when they appear as shown on the map. The speaker's studies were first begun in the southwestern and central western parts of the State, where thrust displacements were clearly recognized and described; but, if possible, the field relations are more involved at the south than along the northeastern border of Lake Champlain.

I wish especially to note that during the season of 1921, in addition to Lower Cambrian and Ordovician fossils found at various places in northwestern Vermont, I found two forms in certain slates in the gorge of the Missisquoi River at Highgate Falls which I identified as *Staurograptus dichotomus* Emmons and a fragment of *Dictyonema* sp., possibly *flabelliforme*. I submitted these specimens to Dr. Ruedemann, of Albany, who thought the supposed *Staurograptus* to be a young *Dictyonema* flattened in the direction of the vertical axis, and that the *Dictyonema* might be a member of the *flabelliforme* group, but also comparable with *D. rectibineatum*. He felt confident that the forms, in the absence of exact specific determination, belonged either to the Schaghticoke (Upper Cambrian) or the Deep Kill (Beekmantown) shale horizons as known in the Hudson Valley.

RECONNAISSANCE OF THE EASTERN ANDES BETWEEN COCHABAMBA AND SANTA CRUZ, BOLIVIA

BY KENNETH C. HEALD AND KIRTLEY F. MATHER

(Abstract)

This region was seen by the authors in December, 1919, during the progress of geological exploration for Richmond Levering and Co., through whose courtesy this paper is available.

The region is one of rugged relief. The dissection ranges from youthful to mature, increasing in intensity from west to east. The controlling drainage was developed on a peneplain, probably of late Tertiary age, small remnants of which remain. This peneplain sloped eastward from an elevation of a little more than 13,000 feet in the vicinity of Cochabamba and Arani to an elevation of about 3,000 feet in the easternmost ridge of the Sierra de Santa Cruz.

Throughout the entire area the rocks are sediments, chiefly quartzites, sandstones, and shales, with minor amounts of limestone, conglomerate, and tillite. They range in age from Devonian to Tertiary and have an aggregate thickness of at least 25,000 and perhaps 40,000 feet.

Throughout most of the area traversed the rocks have been subjected to strong lateral stress and have yielded to it by folding and breaking, so they are commonly tilted steeply and their continuity is broken by many faults. The most intense deformation is not in the westernmost beds, as might be anticipated, but rather about midway between Cochabamba and Santa Cruz. Near Arani, on the west, the beds are only gently flexed and indicate a stress from the southwest rather than from the west. This same direction of stress seems to hold in the more intensely deformed areas.

Presented in full extemporaneously by the senior author, with lantern-slide illustration.

GEOLOGY OF KAUAI, HAWAIIAN ISLANDS

BY N. E. A. HINDS¹

(*Abstract*)

Kauai, northwesternmost of the larger Hawaiian Islands, is the greatly eroded remnant of a single volcanic mountain, much reduced in area and in height. Deep canyons, with steeply cliffed, cirque-like heads, radiate from a central upland which forms the highest part of the island. The canyons open excellent sections of numerous lava flows which dip gently seaward on all sides, thus indicating that the principal vent was near the present island center. Recent lavas have come from subordinate vents, particularly on the southeast coast, and to a more limited extent in the west-central area. As on other islands of the group, ash eruptions mark the closing phases of vulcanism. The later lava flows and the ash eruptions both occurred after most of the erosion and deep weathering to which Kauai has been subjected.

The central peak, Waialeale, 5,180 feet high, is credited with the heaviest known rainfall. This has been of prime importance in the extraordinary canyon development. A residual soil is generally present and varies greatly in depth, as dependent on differences in rainfall in different parts of the island. A discontinuous fringing coral reef is found around most of the shore; on the southwest and west the reef is slightly emerged. A low, wide, very flat plain has developed, surfaced by beach rock, coral-sand dunes, and alluvium. Evidence of submergence is found in the deep alluvium of the flat-bottomed canyons, in recently emerged rock benches, sea caves, and fossiliferous deposits, and in older marine flats and boulder beaches at higher levels.

Presented extemporaneously, with lantern-slide illustration.

¹ Introduced by W. M. Davis.

SECTIONAL MEETING OF THURSDAY AFTERNOON

TITLES AND ABSTRACTS OF PAPERS PRESENTED BEFORE THE SECTIONAL
MEETING OF THURSDAY AFTERNOON AND DISCUSSIONS THEREON

The section for the reading of petrologic papers met about 2 o'clock, under the chairmanship of Vice-President Arthur Keith, with E. O. Hovey acting as Secretary, and listened to the following program:

TUBULAR AMYGDALOID FROM NOVA SCOTIA

BY T. L. WALKER AND A. L. PARSONS

(Abstract)

The writers observed during the past summer a peculiar structure in the basaltic rocks along the south shore of the Bay of Fundy, particularly a short distance east of Morden, in Kings County, and at Margaretville, in Annapolis County. At the former locality the reddish amygdaloid in the low cliffs along the shore is penetrated by vertical cylindrical structures from one to four and a half inches in diameter and at times at least two yards in length. The material of these cylinders is characterized by the presence of white amygdules of zeolites from an eighth to one-quarter of an inch in diameter, which are more abundant near the margin of the cylinders than at the center, while the main mass of the basalt is not marked by any prominent amygdaloidal structure. On a flat surface of basalt below high tide, where the rock was perfectly exposed, the writers observed, within a radius of four feet, twenty-five tubes, eighteen of them from one and a quarter to one and three-quarters of an inch in diameter. The smallest was one inch, while the largest was four and a half inches in diameter. The rock here shows no columnar structure.

Just west of the wharf at Margaretville the basalt is black and very coarsely columnar. The columns, which are quite irregular, are separated by thin seams of silica and are worn deeper at the center by the waves, so as to constitute a series of saucer-like depressions with elevated rims. Here a tubular structure of a different type is noted. It consists of hard vertical cylinders from one to two inches in diameter, sometimes of quartz or quartz and zeolites; at other times of what appears to be a fine-grained, dark basalt with occasional amygdules of quartz. These cylinders are not distributed without regard to the columns, as there is a marked tendency for one core to occur toward the center of each column, although in some instances a column contains several cores, and a few cores may be situated on the margins between two columns. From these two localities How's original specimens of mordenite were obtained. He states that it occurred in cylindrical concretions.

In the former locality the best development of the tubes is in an amygdaloidal flow some thirty feet thick, where they seem to have been the vertical vents for ascending vapors from the wet underlying rocks. The Margaretville type of cylinder might represent the result of liquid magma entering chilled tubes from which the steam had blown out all the liquid magma available.

Presented extemporaneously, with the aid of lantern slides.

Discussed by B. K. Emerson and L. C. Graton.

GRAPHIC STUDY OF IGNEOUS ROCK SERIES

BY FRANK F. GROUT

The paper is to be published in full in this volume of the Bulletin.

Presented by title in the absence of the author.

MOUNT MONADNOCK, VERMONT—A MONTEREGIAN HILL

BY JOHN E. WOLFF

(Abstract)

Mount Monadnock lies at the west bank of the Connecticut River, in Vermont, 6 miles south of the Canadian boundary and opposite the town of Colebrook, New Hampshire. The mountain is oval in plan, three and a half miles in longer diameter; elevation of summit, about 3,140 feet above tide and 2,000 feet above the river at its base. An intrusive mass of alkali-syenite forms the major part of the mountain; the rock is composed essentially of micro-perthite, quartz, albite, hornblende, biotite with granitic or quartz-rich and basic phases. At least one mass of essexite is found deep in the dissected core, and there are camptonite, aplite, and bostonite dikes cutting the syenite. The country rock is a fine-grained micaceous quartzite or quartz-schist, which the igneous mass truncates as a stocklike intrusion. There is no published map of the mountain and only a brief mention of the geology in Hitchcock's Geology of New Hampshire. Lantern slides will show maps of the mountain and distribution of all the Monteregian Hills, and the appearance of the mountain and Connecticut Valley from several sides.

Presented without notes, with lantern-slide illustrations.

Discussed by F. D. Adams, H. S. Washington, J. A. Dresser, Arthur Keith, and E. O. Hovey, with reply by the author.

DISCUSSION

Professor ADAMS: Dr. Wolff's paper is of much interest, both as affording a general view of the Monteregian Hills of New England and a description of a new member of this petrographic province in northern Vermont. Speaking generally, the Monteregian Hills in Canada show a progressive increase in basicity from east to west, and the more acid character of the hills of New England seems to indicate that this change is continuous into the United States. I ask whether, in addition to the main intrusions of Mount Monadnock, there were many dikes. In Canada there were only two of the Monteregian Hills which showed any considerable number of them, namely, Mount Shefford and Mount Royal. About the latter both the surrounding country rock and the intrusions themselves were traversed in all directions by great swarms of dikes. Seven sets of these, each cutting the preceding set, were found in the reservoir extension of Montreal. A great deal of light has been thrown

on the successive stages of volcanic activity of Mount Royal by a careful study made by Dr. Bancroft of the exposures laid bare by driving a tunnel through this mountain recently by the Canadian Northern Railway for the purpose of gaining access to the city of Montreal from the north. In this the successions, not only of the main intrusions, but also of many sets of dikes, have been determined, as well as the existence of extended alterations and new deposits due to vapors and waters given off in the final stages of the volcanic activity.

Mr. DRESSER: I would join in commendations of Dr. Wolff's very interesting paper and ask a single question. Of the Monteregian series of Quebec, only two of the hills, Mounts Royal and Shefford, on the extreme east and extreme west, show a notable development of dikes. The same two hills give strong presumptive evidence of laccolithic structure. Has Dr. Wolff observed evidence of laccolithic structure in Mount Monadnock in which dikes are abundant?

Dr. HOVEY called attention to an acid dike cutting diabase of New Haven region described by him and analyzed by H. S. Washington.

Reply by AUTHOR: In connection with questions as to the possible age of the intrusion, the author mentioned a dike of monchiquite described many years ago by L. S. Griswold as cutting one of the Triassic trap sheets of Connecticut and probably satellitic to the alkaline intrusions of the Novanglian petrographic *petrovince*.

GEOLOGY OF THE PAWTUCKAWAY MOUNTAINS

BY EDWARD S. C. SMITH ¹

(Abstract)

The Pawtuckaway Mountains are a group of three well glaciated hills of the residual type, ranging from eight hundred to one thousand feet in altitude above sealevel, lying in Rockingham County, New Hampshire, 22 miles west of Portsmouth and 16 miles northeast of Manchester.

They consist of the remnants of a deeply eroded igneous body of alkali syenite which is intrusive into a more or less granitic gneiss of undetermined age. The syenite is composed of micropertthite, andesine, hornblende, pyroxene, and biotite essential, with quartz, magnetite, apatite, and zircon accessory. With the syenite occurs also a series of camptonite, tinguaita, and aplite dikes. The camptonite forms a considerable portion of the central part of the mass as well as appearing as dikes, while the other types are present only in subordinate amounts.

Another feature of interest is the rapid weathering of the syenite, which has formed large dunelike deposits of its disintegration products, an unusual sight in New England.

Read by J. E. Wolff in the absence of the author.

¹ Introduced by J. E. Wolff.

EVIDENCES OF ASSIMILATION DURING THE KATMAI ERUPTION OF 1912

BY C. N. FENNER

(Abstract)

In a paper published in November, 1920, evidence was cited for the view that during the eruption of Katmai the collapse of the walls of the former crater and their assimilation by the new magma were essential features of the process that resulted in the formation of the present huge crater-pit. Inasmuch as the properties of the magma implied by this conception are of much theoretical interest, it has seemed desirable to look for further evidences of assimilation. Considerable time has been given, therefore, to a study of samples (collected in the field) of the successive strata of ejected material. Two methods of investigation have been employed: First, the use of a binocular magnifier as an aid in sorting out the different materials of which the ejecta are composed, by which means quantitative expressions for the progressive change in the make-up of the material have been obtained; and, second, a series of chemical analyses has been made, and the linear variation of composition as assimilation progressed which the theory requires has been found to hold true in a very marked manner.

It is believed that this evidence gives strong confirmation to the idea of assimilation on a large scale. Conclusions regarding certain properties of the magma may be derived therefrom.

Presented without notes, with lantern-slide illustrations.

Vice-President Keith withdrew and President Kemp took the chair.

TRIDYMIT-ORTHOCLASE ROCK, A NEW METAMORPHIC ROCK TYPE FROM IMPERIAL COUNTY, CALIFORNIA

BY AUSTIN F. ROGERS

(Abstract)

A banded, porous tridymite-orthoclase rock occurring in a small dome-shaped extrusion is proved by both field observation and microscopic examination to have been formed from a typical rhyolitic obsidian. Intermediate stages in which cristobalite occurs can be recognized. The cristobalite occurs in cavities of hollow spherulites, and also intergrown with orthoclase in solid spherulites. The final stage, which consists of tridymite and orthoclase, is considered to be a metamorphic rock; the metamorphism was brought about by hot gases.

Presented from notes, with lantern-slide illustrations.

Discussed by A. C. Lane.

DISCUSSION

Professor LANE: I would call attention to the fact that in general aporhyolites and felsites would have to be classed as metamorphic if this rock is so classed. Although etymologically correct, I would hesitate so to extend a term which has so generally been confined to rocks which have recrystallized under pressure to which they have yielded.

GENETIC FEATURES OF ALNOITIC ROCKS FROM ISLE CADIEUX, QUEBEC

BY N. L. BOWEN

(Abstract)

Alnoitic rocks at Isle Cadieux, near Montreal, Canada, are found to consist principally of monticellite alnoite. Besides this type, there is a variety consisting almost exclusively of melilite and biotite.

A study of the relations of the minerals indicates that the rock originally consisted of augite and chrysolite and was nearly completely consolidated as such. These minerals were then attacked, with lowering temperature, probably by their own interstitial liquid, as it changed in composition, and they were replaced by monticellite, melilite, and biotite with marialite, perovskite, and titaniferous magnetite as minor products of the reaction. The monticellite is itself replaced by melilite and biotite, and the melilite-biotite rock is the end product of the replacement.

The replacement was accomplished by an alkalic liquid (magma), which formed monticellite from augite by desilicating it, and later gave rise to melilite and the more definitely alkalic mineral biotite.

In an experimental part of the paper equilibrium in mixtures of nephelite and diopside is determined. It is found that from intermediate mixtures forsterite and melilite are the first products to crystallize, and the melilites so formed are analogous to natural melilites in composition and optical properties.

It is thus proved experimentally that nephelite reacts with diopside to form melilite, a reaction analogous to that which is considered to have taken place between augite and alkalic liquid in the natural rocks. This reaction is of the nature of a desilication of the pyroxene. The natural liquid, as modified by the reaction, passed on and possibly gave rise to analcite dikes.

Presented extemporaneously.

SILLIMANITE-SCHIST INCLUSIONS IN GRANITE¹

BY WILLIAM J. MILLER

(Abstract)

While engaged in geological field-work in central Saint Lawrence County, New York, under the auspices of the New York State Museum, during the summer of 1919, the writer found two areas showing a rather remarkable combination of Precambrian rocks. Both areas are within the Russell Quadrangle. The smaller one, near the middle of the quadrangle, is about $1\frac{3}{4}$ miles long, with a maximum width of one-fourth of a mile. This will be referred to as the northern area. The other area, in the south-central part of the quadrangle, is fully $4\frac{1}{3}$ miles long, with a maximum width of three-fourths of a mile. This will be referred to as the southern area. There are many fine exposures in both areas. The main bulk of the rock of each area is medium-grained, pink, moderately foliated granite, consisting chiefly of microcline and quartz in nearly equal amounts, together with from 1 to 3 per cent of magnetite and usually less than 1 per cent each of biotite, muscovite, and zircon.

¹ Published by permission of the New York State Geologist.

Throughout the two areas much of the granite contains myriads of small, nearly white lenses (inclusions) of quartz-sillimanite schist. These lenses, which are of all sizes up to $1\frac{1}{2}$ feet long and 3 or 4 inches thick, are nearly all arranged almost perfectly parallel to the primary foliation of the granite. Most of the lenses are less than a foot long and an inch thick. They rarely, if ever, constitute more than 10 or 15 per cent of the volume of the rock. Local zones parallel to the foliation of the granite are entirely devoid of the lenses, while still other zones contain relatively few of them. Individual zones or belts some rods in width are remarkably uniform as regards numbers, arrangement, and composition of the inclusions, certain definite zones of this kind having been traced almost without interruption along the barren ledges for one-fourth of a mile or more. Not only is the foliation of the lenses and of the granite (and zones of granite) parallel, but also these are parallel to the long axes of the two areas of lens-bearing granite.

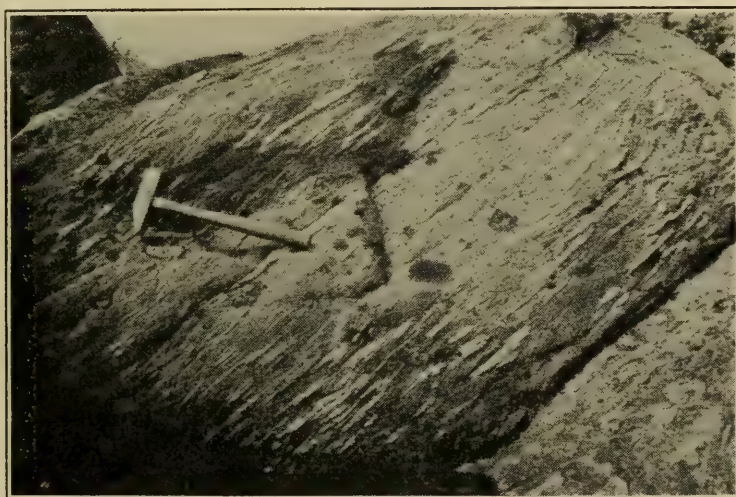


FIGURE 1.—*Sillimanite-schist Inclusions in Granite near South Russell, New York*

Examination of a number of thin sections of the lens material shows it to be very uniform in composition, or about as follows by volume percentages: quartz, 60 to 75; sillimanite, 25 to 40; magnetite, one-fourth to 4; muscovite, one-fourth; and in some cases very little zircon or pyrite. The quartz is granular, while the sillimanite nearly all occurs in the form of needles, many of them singly and many of them in bundles. Many of the bundles consist of crudely parallel needles, while others form more or less curving to plumose bundles. Most of the sillimanite needles lie between the quartz grains parallel to the foliation, but a good many occur as inclusions in the quartz. Some of the sillimanite is in the form of broad, euhedral prisms up to one-half of an inch long.

The material of the lenses is highly foliated or schistose, this structure being notably more highly developed than it is in the adjacent (or inclosing) granite. The lenses are fine-grained to moderately medium-grained, except for the needles of sillimanite which range in length up to one-half of an inch. The magnetite occurs as tiny scattering grains, and the muscovite as tiny flakes.

Many narrow tongues of granite extend partly into the lenses parallel to the foliation; many lenses are cut across at low angles by narrow bands of granite, and some small shreds or tiny lenses have been separated 1 or 2 millimeters from their parent lenses.

The granite maintains its uniformity of grain and color up to the very contacts against the lenses. To the naked eye, these contacts look fairly sharp. Thin sections across the contacts, however, show that, while the composition of the granite is maintained, there are usually some scattering needles of sillimanite in the granite from 1 to 6 millimeters from the contacts.

The inclusions quite certainly represent fragments of the sedimentary Grenville quartzite or quartz-schist formation. This conclusion is based not only on the composition, structure, general appearance of the lens material, and the presence of quartzite in various parts of the quadrangle, but also on the fact that a large exposure of quartz-sillimanite gneiss or schist lies along the western border of the southern area. This nearly white rock forms a high, wide ledge fully one-eighth of a mile long. It is in every essential way like the lens material, except that it carries somewhat less sillimanite and is not so highly foliated. The dip and strike of its foliation are parallel to those of the adjacent lens-bearing granite. Some small pegmatite and silexite dikes cut the ledge parallel to its foliation. A thin section of a specimen from this ledge contains the following minerals by volume percentages: quartz, 77; sillimanite, 20; magnetite, 2; hematite, 1; and a little zircon. Most of the sillimanite is in the form of badly decomposed long prisms, but a good deal of it fills irregular cracks in the quartz.

The history of the above-described phenomena is believed to be essentially as follows: The granite magma entered two long belts of Grenville well bedded quartzite, forced its way between, and wedged apart the layers, and broke them up into myriads of lenses, all of which became arranged more or less perfectly parallel to the magmatic currents. It is a remarkable fact that the granite magma should have so thoroughly and systematically broken the old quartzite formation up into such a vast number of small lenslike fragments, practically none of which are more than $1\frac{1}{2}$ feet long. In many cases narrow tongues of magma were forced across lenses; in many cases narrow tongues of magma were forced lengthwise partly into the lenses, and in some cases tiny lenses or shreds were pulled away from the larger lenses 1 or 2 millimeters into the magma. The lenses were subjected to considerable pressure in the cooling granite magma, and this probably accounts for their highly foliated structure.

Because the quartzite was so thoroughly and rather uniformly separated into small fragments, and because the lenses constitute relatively little of the total volume of rock of each of the two areas, the granite magma, during its consolidation, was little or not affected by the lenses, and it therefore crystallized with very uniform grain, color, and composition, even up to the very contacts against the lenses. The magma appears to have been totally unable to really assimilate any of the quartzite.

Since sillimanite needles commonly lie in the granite several millimeters out from the lens contacts, where they show exactly the same relation to the granite that they do to the lens material—that is, they usually lie between the mineral grains, but in some cases they are inclusions in them—it is prob-

able that the sillimanite did not develop until the intrusion of the magma. This is borne out by the fact that quartzite in other portions of the quadrangle was not observed to contain sillimanite. The sillimanite, which is a simple aluminum silicate, probably developed as a result of contact metamorphism, the alumina possibly having been furnished by the granite magma and the silica by the quartzite. This would explain why sillimanite is more abundant in the lenses than it is in the large adjacent ledge of quartzite, where the effect of metamorphism must have been less. During the intrusion the material of the lenses probably recrystallized, and some of the newly developed sillimanite became included in the quartz, while some was carried off into the borders of the magma. At the same time the tiny grains of magnetite may have been introduced into the quartz-schist from the magma.

It is a puzzling fact that the Grenville quartzite alone, of all the old rocks, was cut to pieces in such a remarkable manner by the granite magma, and this in spite of the fact that there are many large and small areas of very intimately associated Grenville strata and granite or pegmatitic granite in the surrounding country.

The only other case of inclusions of sillimanite-schist in granite observed by the writer in northern New York at all comparable to that above described is on a ridge $2\frac{1}{2}$ miles northwest of Indian Lake village; but there the lenses are not nearly so systematically arranged in the granite, and the sillimanite is associated with considerable feldspar and some garnet.

*PRELIMINARY NOTES ON SOME REGULARLY BANDED ARGILLITES WHICH
SUGGEST SEASONAL DEPOSITION*

BY ROBERT W. SAYLES

(Abstract)

An examination by the author, in January, 1920, of the microscopic sections of shale and slate in the National Museum at Washington with the purpose of finding evidence of seasonal deposition revealed such evidence in a number of cases. In the summer following, Mr. Allyn C. Swinnerton, a graduate student in the Geological Department at Harvard University, was sent by the writer to collect specimens and make a field study of the various argillites chosen for investigation. A short report will be made on the characters of the slates and shales studied. The following argillites show seasonal characters: the Hiwassee slate, of lowest Cambrian or latest Proterozoic age, from southeastern Tennessee; the Athens shale, of Ordovician age, found at Johnson City, Tennessee, and other localities in that region; the Rockmart slate, of Lower Ordovician age, found at Rockmart, Georgia; a Lower Ordovician or Upper Cambrian slate found at Melrose, New York; a slate found at Schaghticoke, New York, and believed to be of the same age as the Melrose slate; and a slate from West Pawlet, Vermont, of undetermined age, but probably Lower Ordovician or Cambrian. Other shales and slates in the National Museum show seasonal characters, but no field study of these with the seasonal theory in mind has been made.

Read from manuscript, with lantern-slide illustrations.

The session adjourned about 4.40 o'clock p. m.

SESSION OF THURSDAY EVENING

ANNUAL DINNER

Thursday evening, in College Hall, the Society held its annual dinner, together with the Paleontological Society, the Mineralogical Society of America, the Society of Economic Geologists, and guests. More than two hundred persons participated. President Kemp presided and acted as toastmaster, calling on Charles Schuchert, John M. Clarke, George Otis Smith, Frank D. Adams, and George D. Louderback for remarks.

PRESENTATION OF LOVING CUP TO PROF. B. K. EMERSON

The feature of the evening was the presentation to Prof. B. K. Emerson of a silver loving cup by his friends in the Society. The address of presentation was made by Dr. John M. Clarke, who said in part:

This Society has come at last to the fountain-head of American geology—Amherst College. Nearly a century ago, while Amos Eaton was inspiring students at the Rensselaer School by his novel modes of teaching, and Silliman the Greater, at Yale, was illuminating the facts and fancies of this science by his brilliant and fascinating deliveries, Edward Hitchcock was actually creating a geological survey of this Commonwealth of Massachusetts and initiating classes of students into the astonishing revelations and practical applications of a new science. It was a difficult field he found here in this Connecticut Valley and its complicated uplands; many different categories of geological facts crowded upon him, but he interpreted them with clarity and with such degree of distinction that he was, in due course, selected by Governor Marcy, of New York, as the first State geologist for that well organized survey; an appointment which he accepted, entered upon, but soon abandoned because that field was too far away from Amherst College—indeed, reason in plenty!

Let us remind ourselves that Edward Hitchcock was a distinguished divine, professor of natural theology and geology and president of this college in the most uplifting days of the last century. This minister of the gospel was boldly entering upon paths lined with harvest fields of truth which to his contemporaries were fields of poison weeds. With equanimity he faced the bigotry of common ignorance and the theological odium; but his students heard and followed him gladly into those days of delightful and romantic adventure over this countryside, when every hill and knoll, each stream and gully, each glacial boulder and picturesque retreat, was baptized by the geologist-president and his classes with ceremonies of address and poem and song: Mounts Castor and Pollux, Mount Pleasant and Mount Pleasant, Mettawampe and Aquilo, the Crescent, the Occident, the glacial stones Rock Rimmon, Rock Oreb, Rock Etam, and so on through a long list of natural monuments—names which should never be permitted to disappear from the map of Massachusetts, for they are storied monuments not only of her science and her scenery, but of one of her great sons.

If I pay this brief tribute to the eminent Hitchcock, it is only to intimate

the influence which helped to mold this other great teacher of our science to whom we are come tonight with our hearts in our hands. Professor Emerson has grasped the very horns of the altar of this science, and as we consider wherein has lain his glowing success as a teacher, let us remember the atmosphere he breathed here in his student days. It was an atmosphere sweetened by the fragrance of a science just bursting into flower, tinged with joyous and natural emotions, but never robbed of its spirit of devotion. Teachers are the personifications of immortality. The men whom Emerson trained, and who have arisen one by one to their own niches in the science, sent out in their turn the influence that here inflated their hopes; and their own students, now turned teachers, too, have sent the echos of the Emersonian days flying—an endless course, like the pursuit of the truth. The footprints in the Connecticut River sandstones were to Longfellow the theme of the Psalm of Life. To Hitchcock they were more than footprints on the sands of time; he saw in the varying depth of these impressions, made heavier on one side than on another, as the creature changed its course or turned a corner, the play of a different muscle and the nerve message from the brain which compelled the muscular motion. There he found, registered in the immortal rocks, the very purpose and impulse of life. And thus, too, the great teacher. While about these tables there are some who owe Professor Emerson a direct allegiance, probably there are none who have not been reached by the ever-widening rings of his influence or been guided by his imprints on the science. We are here tonight to heap upon him our pledges and congratulations, to establish thus a mile-post to mark here the passage of the years. Every rock in the fields of Old Hampshire County claps its hands and the mountains of the Commonwealth break forth into singing, for they are his by a peculiar right and by an emphasis of interest. To him who has sounded their depths and touched their heights, whose eyes have looked in upon the record written in their hearts, whose inspired hammer has loosened their tongues that their tales may be a part of human knowledge and their secrets turned to the advantage of the State—it is to him we make our pledge of admiration and regard. When Edward Hitchcock retired from the presidency of Amherst College, the trustees, not knowing, perhaps, how else to express their substantial regard, presented him with silver plate. So, too, we, in best of heart and with keener sense of our act, ask you to believe this gift, which comes from all of us, is but the miniature symbol of the measure of our regard.

GREETINGS FROM SECTION E, AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

The Secretary read the following telegram:

TORONTO, ONT., *December 28, 1921.*

Dr. E. O. HOVEY,

Geological Society of America, Amherst, Mass.:

Section E sends greetings to G. S. A. Homage to Prof. B. K. Emerson and felicitations to that much loved son of Amherst, Professor Kemp.

WILLET G. MILLER, *Vice-President.*

ELWOOD S. MOORE, *Secretary.*

SESSION OF FRIDAY, DECEMBER 30

The Society met in general session Friday morning at 9.30 o'clock, President Kemp presiding.

VOTE OF THANKS

A hearty vote of thanks was passed to President Meiklejohn and other authorities of Amherst College and the student organizations for the hospitality afforded to the Society in many ways, and to Prof. F. B. Loomis for the perfection of the arrangements for the technical and business sessions, the banquet, and the smoker, which had conduced to the enjoyment of the most largely attended meeting in the history of the Society.

Response was made by Professor Emerson in a few well chosen words.

REPORT OF THE COUNCIL COMMITTEE ON POLICY

By direction of the Council, the chairman of its Committee on Policy read to the Society the report which it had submitted, as follows:

DECEMBER 30, 1921.

To the Council of the Geological Society of America:

The undersigned having been appointed a Committee on Policy on April 20, 1921, to consider certain matters brought to the attention of the Council through letters signed by Ashley, Clapp, De Wolf, Fairchild, Marsters, Pratt, David White, and Fuller, and having given these matters careful investigation, submit the following report of conclusions reached:

1. We believe that the letters referred to, even though comprising criticism and protest, are for the members of the Council and all other Fellows a proper source of gratification, for they indicate a live and healthy interest in the Society.

2. We are convinced that the requirements for Fellowship have not been made more stringent or in any other noteworthy respect changed. Successive Councils seem to have held to much the same standards, and we believe that any committee of seventeen Fellows would, after study, follow the same general course—maintain past and present standards unchanged.

3. There seems to be general agreement among Fellows that a careful and conservative attitude should be maintained in electing Fellows, and that past standards can not be made more "generous" without lowering; that the Fellowship should, so far as possible, consist of workers interested in geology and capable and willing to contribute to the advance of the science. The meetings of a large society which are diluted with non-contributing members tend to become formal, devoid of stimulating discussion and profitable personal contact. The Geological Society of America is and has been from its beginning, in its ideal, a company of workers engaged in developing and fostering geologic science, banded together for mutual encouragement, friendly criticism, and intellectual stimulation.

4. We find that teachers, members of State Surveys, and economic geologists of various kinds have not failed to receive due share of recognition, and, further, that there is no basis for criticism that aristocracy, provincialism, or local or class distinction of any kind has developed in the Society. The value of the teacher to the Society has been recognized by the framers of the Constitution and apparently by all of the successive Councils, for economic geologists and all other kinds of geologists who give promise of cooperating in the advancement of the science have always been welcomed. It has thus far been the experience that the best, though not the only, kind of evidence on this point is the quality of the candidate's publications.

5. The Geological Society of America need feel no concern over possible competing organizations. On the other hand, we may rejoice in the existence and prosperity of such organizations as the American Association of Petroleum Geologists and the Southwestern Geological Society.

6. As to the men outside who should be Fellows, we would remark that some one outside the Council must go to the trouble of proposing their names, and this might appropriately be done by those to whom their names occur. However, it has been found that out of the list of fourteen names of men who should be Fellows, submitted with the letters referred to, only five have been offered to the Council. One was elected in 1916, one in 1920, and two in 1921; only one has been disapproved by three Councils. It would seem desirable to urge upon all Fellows the desirability of seeing to it that names of worthy candidates are submitted, together with full information regarding them.

We realize that there are engaged in professional work many geologists whose ideals and attainments are fully the equal of those possessed by Fellows of the Society, but in general the Council has found no way of appraising such men accurately, in the absence of a record in publication. Even in those cases where the Council may have had evidence of the qualifications of certain of such men, the Fellowship, which holds the final decision, has repeatedly shown its unwillingness to elect men without such printed record.

We believe that every geologist should use his best efforts to change the policy of secrecy on the part of some corporations, and to make it plain that scientific publication and sound private business are not in the least incompatible.

All persons are welcome at the meetings of the Society.

Your committee finds that there has been no appreciable difference in age of elected candidates by decades since the organization of the Society. The average age when elected is between thirty and thirty-two years. Nor has there been any marked change in the numbers of those admitted to the Society.

Respectfully submitted,

EUGENE W. SHAW, *Chairman*.

JAY B. WOODWORTH.

T. WAYLAND VAUGHAN.

GEORGE F. KAY.

GEORGE D. LOUDERBACK.

JAMES F. KEMP, *ex officio*.

Upon the conclusion of the reading of the foregoing report, the Society proceeded with the consideration of scientific papers.

TITLES AND ABSTRACTS OF PAPERS PRESENTED AT THE MORNING SESSION
AND DISCUSSIONS THEREON*FRONT RANGES OF THE ANDES BETWEEN SANTA CRUZ, BOLIVIA, AND
EMBARCACION, ARGENTINA*

BY KIRTLEY F. MATHER

(Abstract)

The following notes were obtained during a reconnaissance of the easternmost ranges of the Andes between 18 and 21 degrees of south latitude, made in January and February, 1920. They are published through the courtesy of Richmond Levering and Company, for whom the geologic examinations were made. Only the southern half of the region traversed has been previously described by geologists.

The mountain ranges along the east front of the Andean Cordillera are long, narrow, sharp-crested ridges, with altitudes of 1,500 to 2,500 feet above their surroundings, which trend in a general north-south direction and are separated by parallel strips of lowland. There is a marked accordance in summit level along their crests from end to end and a regular increase in summit elevation of successive ridges from east to west. Most of the ridges are bordered on either side by steeply inclined hogbacks; others have bold fault-escarpment cliffs along their eastern faces. The Sierra de Charagua, 3 to 5 miles wide and 80 miles long, and the Sierra de Aguarague, of similar width and 170 miles in length, are the most striking of these unique mountain ranges. Others which will be described in this paper, and the locations of which are indicated on the accompanying map, are the Sierra de Florida, the Sierra de Limon, the Sierra de Guarui, the Sierra de Mandiyuti, and the Sierra de Vitiacua.

Certain of the lowland areas between the mountain ranges are occupied by groups of hills or *cuestas*, which ordinarily consist of several westward-sloping hogbacks. The easternmost hogback in each series is abruptly terminated by a prominent fault escarpment; the successive hogbacks generally decrease in elevation from east to west. Individual hogbacks are separated from each other by narrow steep-walled valleys, the eastern wall of which is almost everywhere a dip slope. The most important of these groups of hills are the *Cuestas de Oquita* and the *Cuestas de Pipi*.

The larger streams of this area all flow eastward, with little apparent regard for the present topographic features. The Rio Grande and Rio Pilcomaya, for example, have their sources far to the westward, in the heart of the Cordillera Oriental. Flowing eastward, they cut through the successive sierras and *cuestas* in exceedingly rugged canyons or narrow gorges, which are in sharp contrast to the broad, late-mature valleys which they occupy in crossing the intermontane lowlands.

Obviously, the present drainage system owes its pattern to inheritance from a previous cycle of erosion. Either the modern stream courses were determined before the deformation of the sierras and *cuestas* or the whole region has been peneplained subsequent to that folding and faulting. Several bits of data lend strength to the second of the two alternatives.

The entire region is underlain by sedimentary strata, which may be grouped into the following formations:

Quaternary gravels, sands, clays, and silts.

Unconformity.

Tatarenda formation; soft sandstones, shales, unconsolidated sands and clays, occupying in general the lowland areas; probably Tertiary; 3,000 to 4,000 feet thick.

Unconformity.

Tacuru formation; resistant sandstones and interbedded shales, the "hogback makers" along the margins of the sierras; Late Mesozoic, or possibly in part Early Tertiary; 2,000 to 4,000 feet thick.

Vitiacua limestone and chert; middle or late Mesozoic; 10 to 100 feet thick.

Unconformity.

Bermejo series; Permo-Carboniferous, and possibly in part Early Mesozoic comprising the following formations:

Machareti formation; massive, cross-bedded sandstone and interbedded non-fissile shales and clays; 800 to 1,600 feet thick.

Mandiyuti conglomerate; massive conglomerates, grits, and sandstones, with interbedded sandy shales; predominantly red; in large part fluvio-glacial; 1,500 to 3,200 feet thick.

Oquita formation; extremely variable sandstones and shales, some of which are probably glacio-lacustrine; at many localities including lavender or maroon sandy shales; 1,000 to 2,500 feet thick.

Los Monos shale; blue gray to black, fissile shale, with interbedded micaceous sandstones; base not exposed; more than 1,000 feet thick.

Unconformity. Fault contact.

Totora series; Devonian; including, probably near or at the top, the Espejos formation; dark bluish or greenish black, carbonaceous fissile shale with intercalations of dark, fine grained, brittle limestone in beds two or three inches thick; total thickness unknown.

Structurally, the Front Ranges of the Andes consist of closely compressed anticlines extending for long distances north and south, separated by comparatively broad synclines. Each of the sierras is a long, narrow, sharply folded, doubly plunging anticline, the limbs of which are inclined at angles of 25 to 75 degrees and the axial plane of which is somewhat inclined toward the east. All but one of these anticlines is strongly sheared along a major fault plane which trends parallel to the longer axis of the fold and is situated a short distance east of its crest. The faults are thrusts, with the overhanging wall on the west and with displacements of 3,000 to 10,000 feet. Each of the cuestras, or groups of hogback hills, is a tilted fault block with monoclinical dip toward the west at angles of 20 degrees to more than 70 degrees. Each is terminated on the east by a major fault plane, in approximately vertical position, with the upthrow on the west and with displacement of several thousand feet.

The structure is evidently the result of strong lateral compression resulting from a great thrust which came from the west. The diastrophic movements

were a phase of the building of the Andes system and appear to have been repeated at different intervals during the geologic history of the region. The most important deformation occurred subsequent to the deposition of the Tatarenda formation, but earlier movements took place between the deposition of the Bermejo series and the Tacuru formation, as well as between the laying down of the Tacuru and Tatarenda formations.

Presented in full extemporaneously.

Discussed by Charles Schuchert.

DISCUSSION

Professor SCHUCHERT: Students of South American historical geology will be thankful to Professor Mather for his account of the geology of a formerly unknown region. It appears that his reconnaissance is in an area to the east of the Andean geosyncline where no marine deposits of Pennsylvanian age occur, and this seemingly explains why he found the Lower Devonian overlain directly by Permian continental deposits. The seas of Lower Devonian time were far more widespread than those of the Pennsylvanian.

SOME ASTRONOMICAL TESTS OF THE PLANETESIMAL HYPOTHESIS

BY HARRY FIELDING REID

(Abstract)

There are some remarkable characteristics of the solar system: the forward revolution of the planets and of the satellites, the forward rotation of the planets, the small eccentricities of their orbits, and the nearness of the planes of these orbits to the invariable plane. Some calculations have been made to test the efficiency of the planetesimal hypothesis to explain these characteristics. The hypothesis of the origin of the spiral nebulae and of the solar planets by the approach of a star is briefly considered.

Presented without notes.

MARGINAL BELTS OF THE CORAL SEAS

BY WILLIAM MORRIS DAVIS

Presented extemporaneously, with lantern-slide illustration.

TRANSGRESSIONS, REGRESSIONS, AND SHORELINE DISPLACEMENTS DURING THE PLEISTOCENE

BY CHESTER A. REEDS

Read from manuscript.

OLD AND NEW STANDARDS OF PLEISTOCENE SUBDIVISION

BY HENRY FAIRFIELD OSBORN AND CHESTER A. REEDS

Read in abstract from manuscript by the junior author.

Discussed by Frank Leverett, W. M. Davis, H. F. Reid, and Ernst Antevs.

IS THE PRESENT THE FIRST OF A NEW CHAPTER?

BY ALFRED C. LANE

(Abstract)

Wells' History, page 12, considers the Quaternary as the last page of a chapter. But if with Schuchert we consider periods to be marked off by the alternate domination of forces of elevation and degradation, the beginning of the period being placed when forces of degradation begin to get the upper hand, there are reasons for considering the present the beginning of a new chapter.

The age of the earth comes out so much less by using present erosion, deposition, or accumulation of soda in the ocean than by the methods based on the rate of uranium decay, that it is suggested that the former rates are abnormally active, as would be the case when the continents stood relatively high. On the other hand, the presence of the continental shelf and the widespread occurrence of drowned shorelines suggest that the forces of degradation are once more gaining the upper hand. Unless the present is an interlude therein, the Glacial period would seem to correspond to the Permian Glacial period and the present to the Triassic.

Read from manuscript, with lantern-slide illustration.

HOT SPRINGS OF LASSEN NATIONAL PARK

BY A. L. DAY AND E. T. ALLEN

(Abstract)

An account of a detailed chemical and physical study of the hot springs and "mud volcanoes" of the localities known as "The Geyser," "Lake Tartarus," "Devil's Kitchen," "Bumpass' Hell." Chemical analyses of the liquid, gaseous, and solid ingredients will be presented, together with an account of conditions favorable to the formation of pyrite and other minerals found in the springs. The temperatures of the springs and their seasonal variations are included.

Presented extemporaneously by the junior author. Lantern slides were used.

RECENT ERUPTION OF LASSEN PEAK

BY A. L. DAY AND E. T. ALLEN

The volcanic phenomena accompanying the eruptions of 1914 and 1915 will be described, and analyzed with the help of photographs, together with appropriate comparisons with recent volcanic activity elsewhere and some inferences regarding proximate causes. The paper is related to the preceding, and the matter is treated both from the physical and chemical viewpoints.

Presented extemporaneously by the senior author. Lantern slides were used.

*SURFACE FUSION OF LAVA*BY J. S. DILLER¹

Some time ago there came to the U. S. Geological Survey in Washington, through the U. S. Department of Agriculture, from Dr. Calderón, of San Salvador, Central America, samples of lava erupted in that region June 7, 1917, from the crater of El Pinar, San Salvador, Central America. They illustrate in a striking manner the refusion of lava by included gases escaping during eruption, after coming into contact with the air at the surface.

The samples of lava were collected near the surface of the lava-flow, in pockets of scoria which Dr. Calderón says were formed by the escape of gases, especially on all steep slopes where the lava formed cascades.

The largest piece of lava received from the eruption of 1917 is approximately 7 inches in length, breadth, and thickness, and its two portions are quite unlike, as shown in the illustration, figure 1. One portion is red, bounded by surfaces of fractures. It is of light weight, wholly vesicular, much like pumice; vesicles generally fine and irregular, seldom large. The other, or lower, portion of the specimen is black, generally very vesicular, but the vesicles are round and vary in size. The striking feature of this portion is its flow surface. Much of it is in the icicle-shaped bodies hanging from the other portion like stalactites. The molten lava dropped in small streams from some of these bodies and coiled on the bottom of the pocket. Both portions are basaltic lava and under the microscope show numerous minute plagioclase crystals in a globulitic base which contains much clear glass.

The contact between the two portions is well marked. It is irregular and evidently, as it is the limit of the flow lines, it marks the limit of fusion.

Judging from the composition and relation of the two portions, there seems to be good reason for believing that the black, lower portion of the specimen was formed by the fusion of the red, upper portion by hot gases in a lava pocket. This opinion is corroborated by the fact that a piece of the red portion fused before a blast lamp becomes black.

Judging from the statement of Dr. Calderón, the specimens were collected in the lava-flow only where it descended in cascades. The included gases thus liberated from the breaking, cascading flow mixed with air in the lava pockets and apparently produced sufficient heat to melt the adjoining lava of the same flow. This phenomena is similar to that observed by Day and Shepherd at Kilauea, in Hawaii, and described before this Society in 1913.

In the small lava-flow from the great eruptions of Lassen Peak, California, May 19 and 22, 1915, there are samples of surface fusion and flowage (figure 2) quite analogous to that just noted from San Salvador. The lava from Lassen Peak, however, is dacite and much more siliceous than the basalt of San Salvador. Therefore it was much more difficult to melt, and when melted was much less fluent. Only a thin surface coating of the dacite was melted locally and flowed among the unfused portions.

The surface melting of the dacite took place about the close of the great eruption, in May, 1915, when the body of rising volcanic gases pushed up the more or less softened lava plug that occupied the throat of the volcano until,

¹ Publication approved by the Director of the U. S. Geological Survey

by spreading, the crater was filled and overflowed, liberating the most remarkable blasts of hot gas, which were shot down the slope as at Martinique, completely devastating its path.

That the extruded lava was softened by heat and rendered viscous is shown



FIGURE 1.—*Basaltic Lava from San Salvador, Central America*

This basaltic lava was erupted by the Crater El Pinar of San Salvador volcano June 7, 1917, in the republic of San Salvador, Central America.

Dr. S. Calderón sent the specimens to Washington, and states that they were "collected in pockets of scoriæ formed by the escape of the gases, being found on all very steep slopes where the current of lava formed cascades."

It is believed that the hot gases escaping from the lava-flow into the pockets met the gases of the air and reacted so as to become hot enough to melt the adjacent lava.

The upper portion of the specimen is dull red. It is a part of the lava-flow the lower portion of which has been melted by the hot gases in a pocket.

by the fact that the steam-torn lava was bent during the eruption. Portions of the bent lava were broken, but the continuity of the mass indicates that most of the lava at the time of its eruption was softened by heat to a highly viscous condition.

Additional evidence of viscosity of the lava at the time of the great eruptions, May 19 and 22, 1915, is furnished by some of the bombs ejected at that time. No such bombs had been found in that region before the great eruption, and the ones in question were certainly ejected during that eruption. The bomb studied was slightly oblong-round and about three feet in diameter. It was completely enveloped in a bread-crust surface and when broken was



FIGURE 2.—*New Lava from Lassen Peak, California*

This new lava, which erupted May 22, 1915, overflowed the crater rim northeast into the head of Lost Creek.

found to contain a number of compact, dark inclusions, apparently early secretions from the magma. As the soft material of the bomb, when relieved from pressure by being ejected, enlarged radially by the expansion of the contained gases, it elongated the vesicles in the viscous lava and drew away from the solid inclusion on lines perpendicular to the bread-crust surface, showing clearly that at the time of its ejection the mass of the boulder was viscous.

A SOURCE OF HEAT IN VOLCANIC ACTIVITY

BY LEASON H. ADAMS¹

(Abstract)

The object of this note is to direct attention to the thermal effect accompanying extrusion as a competent source of heat for volcanic phenomena.

¹ Introduced by H. S. Washington.

When pressure on a liquid or solid is released in a certain way, namely, by extrusion through a small orifice, the temperature is raised very considerably. Thus, ordinary rock material, if extruded from a pressure corresponding to a depth of 20 kilometers, would heat itself up nearly 200 degrees centigrade above its original temperature. Moreover, the process may accelerate itself and it may be intermittent in character. This kind of a process would seem to account for certain types of volcanic activity without postulating a liquid reservoir.

Read from manuscript by H. S. Washington in the absence of the author.

The preceding four papers were then discussed by James F. Kemp, H. F. Reid, and A. L. Day.

DISCUSSION

Professor KEMP: The speaker referred to the question of the composition of the explosive gases described by Dr. Day and asked if further details of their composition could be given. Speaking of the low temperature, he asked if any such effect was produced in the expansion on emission as is met in the use of compressed air. When the compressed air escapes from an engine or rock drill, there is a great lowering of temperature on expansion, sometimes enough to condense and freeze any water vapor in the air, if the expansion is not adjusted to allow for it.

Dr. DAY: (In reply to Dr. Reid.) To account for the very superficial combustion of dead leaves and dried twigs on the hillside facing the mountain, it does not seem to me to be necessary to invoke any other agency than the momentary increase in the time of exposure to the hot blast caused by the momentary interference of the opposing hill to its passage.

(In reply to Dr. Kemp.) I am sorry that in closing my address so hastily I omitted to state my conclusion regarding the composition of the blast. In my opinion, it consisted of ash-laden steam with practically no accompaniment of the usual chemically active gases, such as HCl, H₂S, SO₂, and the like.

USE OF FORAMINIFERA IN DETERMINING UNDERGROUND STRUCTURE, ESPECIALLY IN PETROLEUM MINING

BY J. A. CUSHMAN

(Abstract)

In Tertiary and Cretaceous formations of marine origin foraminifera are usually present and often abundant. An intensive study of the foraminiferal faunas of these formations in the American Gulf Coastal Plain and other regions bordering on the Gulf of Mexico and the Caribbean has shown that the faunas of the various members of these formations are easily recognizable. On account of the small size, most of the foraminifera escape injury in drilling operations. For this reason and from their abundance (sometimes as many as one hundred species in a cubic inch of material), they are of more importance in determining the strata penetrated by the drill than any other group of organisms. When well logs can be examined it is possible to determine

anticlinal structures which may not be recognized at the surface. In a similar way the dip of the beds associated with salt domes may be indicated from a study of well drillings. Each special field area has problems of its own, which should be carefully studied before attempting to apply data from other areas. The existence of underground faults may likewise be indicated by a study of the foraminifera encountered in drilling across such structures.

Presented by title in the absence of the author.

The session adjourned about 12.30 o'clock p. m.

SESSION OF FRIDAY AFTERNOON

The meeting for the reading of petrologic, mineralogic, and economic papers met Friday afternoon, under the chairmanship of President Kemp, E. O. Hovey acting as Secretary.

TITLES AND ABSTRACTS OF PAPERS PRESENTED AT THE AFTERNOON MEETING AND DISCUSSIONS THEREON

DECCAN TRAPS AND OTHER PLATEAU BASALTS

BY HENRY S. WASHINGTON

(*Abstract*)

The Deccan traps are a thick series of horizontal basaltic flows which issued from fissure eruptions in the late Cretaceous and now cover about one-seventh of the peninsula of India. They are of very simple and uniform mineral composition and ten analyses show that they are all much alike chemically. They are quite typical basalts, except in their high content in iron oxides, mostly ferrous, which is characteristic of them. Most of them contain considerable glass. With the Deccan traps are compared the basalts of other extensive "plateau eruptions," especially those of the Oregon region, the North Atlantic (including Iceland), Siberia, and Patagonia, many new analyses of the rocks of which are given. All these plateau basalts resemble those of the Deccan in their high iron content and simple mineral composition. The Archean flows and sheets of the Lake Superior region and the Triassic traps of the Eastern States appear to be very similar.

It is suggested that the high iron content accounts for the great fluidity of these basalts at the time of extrusion, which is characteristic of all the flows, enabling them to spread in horizontal sheets over very extensive areas and for long distances. The same chemical feature may also account for the quiet character of their extrusion. The plateau basalts, in general, would appear to represent a special kind of basaltic rocks, and the bearing of this on the idea of Atlantic and Pacific series, as well as on the question of the gravitational distribution in the earth's crust, is briefly discussed.

Presented extemporaneously. Illustrated by lantern slides.

GEOLOGY OF THE GUILFORD, CONNECTICUT, QUADRANGLE

BY WILBUR G. FOYE

(Abstract)

The Guilford Quadrangle is situated immediately east of the New Haven Quadrangle and forms a position of the area whose geology will be described in the projected New Haven folio.

A large batholith of tonalite, whose center lies in the town of Killingworth, is the dominant feature of the structure of the area. A border of gneiss, succeeded by a border of metamorphic sediments, dips gently away from the central batholith on all sides.

At the south of the area the tonalite, previously rendered gneissic, has later been altered by impregnation by a granite allied to the Sterling gneiss of Rhode Island.

Presented extemporaneously.

Discussed by B. K. Emerson.

DISCUSSION

PROFESSOR EMERSON: I wish to express appreciation of this paper. The Walker Building, next, east, to our meeting place, is a fine example of the Mourn granite. The trimmings of Williston Hall, where we have held our meetings, is of a more gneissoid type of the same age, from Pelham, east of Amherst. The Amherst schist had better have been named the Wilbraham schist, as the good outcrops in Amherst have been quarried away or covered.

*JASPEROID OF THE JOPLIN DISTRICT, MISSOURI, KANSAS, AND OKLAHOMA*¹

BY W. S. TANGIER SMITH

(Abstract)

In this paper, following an outline of the geology of the Joplin District and a brief account of the characters of the jasperoid, the various hypotheses concerning its origin are reviewed and facts are presented in support of the view that the rock is a replaced limestone. This is assumed as a basis for all the conclusions in the remainder of the paper.

The hypothesis that the chert breccias of this district are a residual from the solution of limestone is rejected for the reason (among others) that the conditions show most of the limestone originally associated with the chert of the ore bodies to have been replaced by jasperoid or dolomite, instead of being lost by solution, leaving cavities. The occurrence of the jasperoid as a cement to the chert breccias is explained as the result of flowage of the limestone at the time of the brecciation of the cherts, and evidence is presented that in the sheet ground also the limestone which the jasperoid replaces has undergone at least slight deformation by shearing and flowage prior to its silicification.

The brecciation of the chert and the flowage of the limestone are both considered to be the result of stresses developed within synclinal folds of the unusually competent Grand Falls chert. The breccias are believed (on ample

¹ Read before the Cordillern Section of the Society March 26, 1921.

evidence) to have been formed chiefly on the flanks of faulted and collapsed anticlinal arches and domes resulting from the synclinal folding. The fine, or lamellar, banding occasionally noted in jasperoid is explained as the result of differential replacement of laminated limestone by quartz. The replacement of limestone by dolomite instead of jasperoid, which is found in parts of the district, is accounted for by selective metasomatism, due chiefly to slight differences in the character of the deformation of the limestone prior to replacement.

From a consideration of the chemical aspects of the problem of limestone replacement and ore deposition (with special attention to the underground waters of the region) the deduction is drawn that the replacement by jasperoid involved dilute solutions of silica and carbon dioxide, the latter having resulted largely from reaction between sulphate in solution and hydrocarbons contained in the limestone, and from the reduction and precipitation of the metals as sulphides. The bitumen of the ore deposits is considered a residual from these reactions.

The chemical conditions favorable to the metasomatism of the limestone and to ore deposition being evidently widespread, while the only structural feature which appears to be common to all the ore deposits is the deformation of the limestone, it is concluded that this deformation has been the controlling factor in the replacement of limestone by both jasperoid and dolomite, as well as in the deposition of the sulphides of the metals.

Since the term *jasperoid* is not entirely satisfactory for such rocks as are here described, and since replacements of limestone or dolomite by silica form a well defined type, of relatively common occurrence, the name *silekite* (sil'-e-kite) is proposed for such replacements, whether crystalline or chalcedonic.

Presented by title in the absence of the author.

TRANSITIONAL COALS AND THEIR BEARING ON HYPOTHESES OF THE
ORIGIN OF COALS

BY EDWARD C. JEFFREY

(Abstract)

By improvements in methods the author has been successful in making sections showing the transition from one type of coal to another. It is well known to those who have given any attention to the study of coals that not infrequently bituminous coal of black and shiny aspects passes abruptly into dull lustered cannel. Similarly, bituminous coal passes into oil rock. (Notably is this the case in certain Australian coals.) It is generally assumed that most coals with a glistening or predominantly glistening aspect are formed *in situ* and on a more or less solid substratum. Such coals are commonly designated humic coals at the present time. In contrast to these are the oil shales and cannels, characterized by a dull luster. These are universally admitted to have been laid down by sedimentation in open water. They are currently known as sapropelic, or aquatic, coals. The study of the transition from one type to the other clearly shows that the so-called humic, or terrestrial, coals are practically identical in organization to the so-called sapropelic,

or aquatic, coals, and consequently are of similar origin. The conclusion is reached that all the main types of coal represent organic deposits slowly accumulated under open water in more or less tranquil lakes, lagoons, or estuaries. The *in situ* hypothesis of the origin of coal is based on complete ignorance of the organization of coal, which has been revealed by improved methods in recent years.

Presented without notes, with the use of lantern slides.

*ORGANIZATION OF PENNSYLVANIAN ANTHRACITE AND THE PEAT
HYPOTHESES OF THE ORIGIN OF COAL*

BY EDWARD C. JEFFREY

(Abstract)

The author, after repeated efforts, has devised methods of making transparent sections of Pennsylvania anthracite. Photomicrographs of these are shown and conclusions are drawn as to the conditions of formation of anthracite. The bearing of the facts, for the first time set forth, upon the hypothesis of the derivation of anthracite as the end product of the metamorphosis of peat is discussed.

Presented extemporaneously. Illustrated by lantern slides.

Discussed by James F. Kemp, with reply by the author.

ORE DEPOSITS OF LEADVILLE, COLORADO

BY G. F. LOUGHLIN

(Abstract)

A summary of features in the new Leadville monograph, namely, the work of the late Prof. J. D. Irving, that differ from those in Emmons' original monograph. The principal topics considered are (1) pre-mineral deformation, including igneous intrusions, fissuring, and normal faulting and overthrust faulting; (2) ore deposition and the relations of the three classes of deposits (contact metamorphic bodies, "blankets," and fissure veins); (3) post-mineral faulting; (4) ore reserves.

Presented by title in the absence of the author.

ANTIMONY MINES OF SHIU CHOW, CHINA

BY GEORGE D. HUBBARD

(Abstract)

Shiu Chow is located at the north end of a railroad leading north from Canton toward Hankow, in the province of Kwangtung. The topography is advanced mature in Paleozoic rocks ranging in age probably from Ordovician to Carboniferous, inclusive.

The ores are stibnite below and cervantite in the weather zone. The former

are associated with coarse crystalline calcite, through which the crystals run in metallic shiny prisms in every direction. The ore also impregnates the limestone adjacent to the main vein. It seems to have been deposited by ascending waters which had risen through the Ordovician (?) beds and spread out below the overlying shales. No igneous rocks were found in the vicinity. Mining is just started in the vein itself. Earlier work is in the float only.

The furnace for reducing the ore is a small brick reverberatory hand-feed, wood-burning affair.

The paper summarizes briefly what is known of other Chinese antimony mines and their geologic relations.

Presented by title in the absence of the author.

SOURCE OF THE SULPHATES IN THE SALINA BEDS

BY DAVID H. NEWLAND

(*Abstract*)

The calcium sulphate present in the Salina formation throughout much of its areal extent is considered to be an integral part of the stratified series, deposited under surface conditions along with the limestones, salt, and shales. No substantial evidence of secondary origin of the sulphate through the decomposition of limestone by sulphuric acid waters has yet been deduced or seems likely to appear, in view of the extensive explorations that have already taken place. Consequently, it seems hardly proper to consider the salt and sulphate minerals as unconnected occurrences. It is likewise quite certain that most of the calcium sulphate exists in the anhydrous form rather than gypsum. The gypsum deposits are superficial, arising from the hydration of anhydrite, which predominates below a depth of a few hundred feet.

Evidence of the primary nature of the sulphate is: (1) The principal deposits have the shape of thin seams interstratified in nearly horizontal limestones and showing no marked irregularities of contact above or below, except as these arise from solution. (2) The more substantial beds spread over areas of many acres or even several square miles and terminate by gradual wedging out. Their position in the stratified series is constant. (3) The deposits are remarkably free of foreign inclusions, though they may carry disseminated impurities of calcarous or clayey nature. No residual bodies of shale or limestone occur in the mined deposits. (4) The beds are found below the zone reached by ground-water circulations, for they persist at depths where the rock-salt still remains in force. (5) Metallic sulphides are not found in the Salina in sufficient amount to account for the sulphate locked up in the two minerals, and there is strong evidence to indicate that they were never present.

The irregularities exhibited by gypsum, as described or depicted in early reports, occur on the outcrop, where solution is at work, or more rarely may be attributed to deposition by water of the sulphate derived from the lower zone. To the latter agency is also to be ascribed the veins and cavity fillings that accompany the beds.

Presented by title in the absence of the author.

FLOODING OF OIL WELLS BY FRESH WATER

BY THOMAS C. BROWN

(Abstract)

This paper explains the bad effects of fresh water on the production of oil wells as due to capillary action produced by the greater surface tension of the fresh water.

Presented by title in the absence of the author.

The section adjourned about 4.30 o'clock.

SECTIONAL SESSION OF FRIDAY AFTERNOON

The section for the reading of the remainder of the stratigraphic and paleontologic papers met Friday afternoon, under Arthur Keith as chairman and J. J. Galloway as secretary.

TITLES AND ABSTRACTS OF PAPERS PRESENTED AT THE AFTERNOON
SESSION AND DISCUSSIONS THEREON*ORISKANY OF OKLAHOMA*

BY CHARLES SCHUCHERT

(Abstract)

Recently late Oriskany deposits have been made known in Missouri by Weller and by Dunbar in western Tennessee. Now the upper part of the Saint Clair limestone, heretofore regarded as Middle Silurian, is seen to be Oriskany in development and much like that of Missouri.

Presented in abstract from notes.

Discussed by Arthur Keith, with reply by the author.

AGE OF THE TALLADEGA PHYLLITE

BY WILLIAM F. PROUTY

(Abstract)

A considerable portion of the Talladega phyllite (Ocoee), as exposed in Clay County, Alabama, is shown to be of Carboniferous age, both Mississippian and Pennsylvanian being represented. It is also highly probable that a number of areas of rock lying to the southeast, in the more highly metamorphosed mica schist and gneiss area, are also of Carboniferous age.

Presented by title in the absence of the author.

CONSTITUTION OF THE OHIO BLACK SHALES

BY GEORGE H. CHADWICK

Presented extemporaneously.

Discussed by Arthur Keith, Charles Schuchert, J. W. Beede, and T. W. Vaughan.

DISCUSSION

Professor SCHUCHERT: The speaker agrees with Doctor Keith that the stratigraphic correlations made by Professor Chadwick could not have been made on the basis of fossils alone. We see here the fine results attained when fossils are used to check the tracing of formations from place to place. This detailed local tracing of the various formations leads to the fixing of times of erosion and overlap, and to a determined and provable stratigraphy and paleogeography.

VOLCANIC ASH BED IN THE ORDOVICIAN OF TENNESSEE, KENTUCKY, AND ALABAMA

BY WILBUR A. NELSON

(Abstract)

A discussion of the occurrence of a deposit of volcanic ash known as bentonite and consisting mostly of leverrierite. The bed occurs at the top of the Carters formation of the Black River group of the Ordovician. Descriptions of outcrops from Birmingham, Alabama, on the south, to Highbridge, Kentucky, on the north, will be given and the economic possibilities of this deposit discussed.

Read from manuscript.

Discussed by Charles Schuchert, T. Wayland Vaughan, and G. H. Ashley.

DISCUSSION

Professor SCHUCHERT: The speaker wishes to congratulate State Geologist Nelson on his very remarkable discovery of this widely spread ash bed of Lowville age, covering an area estimated at more than three hundred thousand square miles. As the time of this ash-spreading was very limited, possibly of only a few years' duration, and since it is the only one known in the Mohawkian series, this ash zone is one of the finest possible time-markers, more limited by far than any faunule can be.

Dr. VAUGHAN mentioned the value of widely extended thin ash beds in precise correlation.

Dr. ASHLEY called attention to the possibility of a distribution to account for the occurrence of thin clay beds making pastings in coal beds, some of which maintain uniform thickness over thousands of square miles.

STRATA NEAR STUART, IOWA

BY JOHN L. TILTON

(Abstract)

In the early work on Guthrie County the strata near Stuart were assigned to the Kansas City division of the Missouri stage, as if a continuation of the strata well exposed in the quarries at Earlham, a few miles to the east.

The present writer has found that the Thurman-Wilson fault, which he had traced through Montgomery and Cass counties into Adair County, extends between Earlham and Stuart, the upthrow on the Stuart side, and the strata there and to the west to be of the lower Des Moines stage (Appanoose or Henrietta) and not Kansas City strata. This area is thus divided by a fault, which accounts for the peculiar distribution of coal on the two sides of the fault and remakes the geological map of Iowa in a considerable area.

Read from manuscript. Illustrated by a wall map.

ENVIRONMENT OF THE EARLY PERMIAN INSECTS OF KANSAS

BY CARL O. DUNBAR

(Abstract)

During the summer of 1921 the speaker restudied Sellards' unique fossil insect locality in Dickinson County, Kansas. A very large collection of insects was secured and the associated geologic phenomena were studied. The occurrence of the fossils will be described and conclusions drawn as to the environment in which these insects lived.

Presented without notes, with lantern-slide illustration.

Discussed by J. J. Galloway, Charles Schuchert, and George H. Chadwick.

*SOME CAVERN DEPOSITS IN THE PERMIAN IN WEST TEXAS*¹

BY J. A. UDDEN

A few years ago I reported the presence of some Cretaceous foraminifera that occurred in samples from a boring made near the center of the south line of survey 24, block 110, in the public-school lands in Culberson County. These were found below Permian limestones at a depth of 141 to 144 feet, and again at a depth from 180 to 213 feet. Textularias, Globigerinas, Bulimina, Anomalina were noted. Dr. Joseph A. Cushman, who kindly examined the material, said that these fossils were more likely to be Mesozoic than Paleozoic. The fossils came from marly shale and sand and were associated with some pebbles of quartz and some sandstone. The geology of the region was but little known at that time and the explanation of the occurrence of Mesozoic fossils in what was known as a late Permian series of rocks remained a puzzling problem.²

¹ Manuscript received by the Secretary November 1, 1921.

² J. A. Udden: The age of the Castille gypsum and the Rustler Springs formation. Am. Journ. Sci., vol. 40, August, 1915, pp. 151-156.

In the course of examination of subsurface material done last summer in the laboratory of the Bureau of Economic Geology of the University of Texas, a new discovery of Cretaceous fossils occurring in the same manner in the Permian was made by Dr. W. M. Winton. These samples were from the Slayden No. 1 well, drilled by the Lewis-Jones Syndicate, in the northwestern quarter of section 25, block 101, in Culberson County. It is located about 15 miles southwest of the Troxel well and a few miles northeast of the center of Culberson County. In this boring the drill first passed through a little more than 60 feet of Pleistocene material. At 80 feet the rock consisted of limestone. Then for nearly 300 feet the bedrock consisted of dolomite, gypsum, and some anhydrite, certainly Permian in age, down to 380 feet. From this depth down to 500 feet below the surface the drill passed through beds consisting of a mixture of clay, shale, some gypsum, gravel, and sand. Below this depth again the samples examined extended down to 733 feet, and these consisted almost entirely of dolomitic limestone of the type of the Permian rocks found in the region. The general section of the boring can be briefly described as follows:

General Section of the Material penetrated in Sayles No. 1, Culberson County

	Feet
Surface soil, gravel and sand, evidently Pleistocene.....	0-70
Limestone, dolomite, and gypsum, Permian.....	70-380
Marl with anhydrite and gypsum.....	380-390
Marly material, clay, shale, sand, and gravel. Much of the gravel consisted of worn and angular fragments of dolomite, worn and angular pebbles of flint and pieces of sandy limestone and sandstone of a chalk-like rock; also pebbles of quartz and "Red Beds" sandstone, glauconite, and pyrite. In this material Dr. Winton identified fragments of oyster shells, <i>Gryphæa washitensis</i> (Nepionic), <i>Arca washitensis</i> (in pyrite), cidarid spines, <i>Nodosaria texana</i> , <i>Textularia globulosa</i> , <i>Anomalina</i> , <i>Globigerina</i>	390-500
Dolomitic limestone, Permian.....	500-733

A closer examination of the material penetrated between the depths of 390 and 500 feet makes it evident that it is a deposit in a cavern. It consists mainly of Cretaceous and Permian debris and is entirely unrelated to the general section of the Permian. The writer takes it to be of Pleistocene age. There seems to be a mixture of different kinds of Cretaceous material, representing mainly the Georgetown or its equivalents. It is, of course, possible that a cavern deposit might have been made at the time of the advance of the Comanchean sea. The general geological conditions suggest that several hundred feet of the Permian have been eroded in late Tertiary or Pleistocene time, and that the base of the Comanchean lay much higher up than the present surface of the land. If such was the case, it would be difficult to explain the transportation of material to such great depth below the advancing sea. It also appears that the material represents more than one formation of the Cretaceous. To the present writer it seems most likely that the cavern now filled had developed after the elevation of the Permian series to its present height, which probably took place at the end of the Mesozoic age or later, and

that the filling represents a time when the Cretaceous sediments were still present over a part of this region.

This is one of the few instances that have come under my observation, where cavern deposits of such size have been penetrated by borings and where it has been possible to identify them as such. Another instance the present writer had occasion to describe was in the Silurian in the Atlantic Brewery well drilled in Rock Island, Illinois. In this case it was clear, however, that the age of the deposit was that of the base of the overlying formation, the Pennsylvanian, and the filling itself in this case was quite ancient.³ The finding of this last deposit in the Sayles well gives a satisfactory explanation of the deposit found in the Rustler Springs formation in the Troxel well, already referred to. The associated materials in which the Cretaceous fossils were found were also, in that case, such as to suggest a cavern deposit, although this was not recognized at the time the first examination of these borings was made.

Presented by title in the absence of the author.

PALEOZOIC-MESOZOIC CONTACT THROUGHOUT WYOMING

BY S. H. KNIGHT¹

Presented extemporaneously.

*STRATIGRAPHY OF THE LOWER OREODON BEDS OF THE SOUTH DAKOTA
BIG BADLANDS*

BY WILLIAM J. SINCLAIR

(Abstract)

The Oreodon beds (Middle Oligocene) in the Big Badlands rest with erosional unconformity on the Titanotherium beds (Lower Oligocene) and consist of clays, often color-banded, of which the lower 40 feet, more or less, are of pinkish-gray color. The so-called "Turtle Oreodon layer," or "Red layer," of collectors constitutes the *Mesohippus bairdii-Oreodon culbertsoni* zone par excellence.

In its upper part there is a zone of rusty nodules, usually but a few feet thick, which is believed to owe its origin to ground water rising surfaceward by capillarity, at times of decreased precipitation and more intense surface evaporation, and depositing its limy content in the clays, at or near the surface, either with or without an organic center for the nodules. This supposedly climatically controlled horizon is constant in position over an area 50 miles and more across and has been used by the Princeton 1920 and 1921 expeditions as a datum plane for faunal and stratigraphic studies. A second, quite narrow zone of nodules lies some 60 feet higher than the one first mentioned and seems to be similar to it in origin. Both are richly fossiliferous, but the second has not been traced over so great an area as the first.

³ J. A. Udden: An account of Paleozoic rocks explored at Rock Island and vicinity. 19th Annual Report of the U. S. Geological Survey, part 2, pp. 829-849. Compare also Geology of Iowa, James Hall, vol. i, p. 130.

¹ Introduced by James F. Kemp.

The Oreodon beds are believed to have been deposited over a baseleveled plain by streams. As a result of fluctuations in run-off, possibly climatically controlled, the fine sediment spread over the plain was cut across at intervals by stream channels filled with coarse detritus, the *Metamynodon* channels, which may interrupt the lower zone of rusty nodules or lie below or above it. The whole sequence of beds suggests climatic control. Local beds of nodular limestone produced by blue-green algae at intervals throughout the formations.

Since both nodular zones afford abundant fossils, collecting during the past two years has been largely confined to them. Their narrowness seems to assure the contemporaneity of the forms obtained from each. The lower nodular zone probably afforded the fossils collected 70 years ago by T. A. Culbertson and others, as it is exposed at his localities and still abounds there in fossil turtles, as described in his diary.

Presented in abstract from notes, with the use of lantern-slide illustration.

Discussed by W. D. Matthew.

DISCUSSION

Dr. MATTHEW: Dr. Sinclair's work is of fundamental importance in the exact correlation and succession of the later Tertiary mammal faunas. In attempting to obtain exact faunal results it has been found that more precise and thorough stratigraphic studies in the principal fossil formations were essential. This could best be begun with the White River Oligocene in its typical exposures in the Big Badlands of South Dakota. Dr. Sinclair's paper shows the great progress already made in this formation.

DISCUSSION OF THE PLEISTOCENE AND ITS VERTEBRATE FAUNAS

BY OLIVER P. HAY

(Abstract)

1. Limits of the Pleistocene.
2. The Pleistocene of the Nebraskan glacial stage.
3. The early Pleistocene a time of widespread elevations of the continent.
4. The early Pleistocene a time of commingling of faunas from widely separated origins.
5. The Pleistocene not a time of rapid evolution of the vertebrates, but of extensive destruction of species.

Read from manuscript.

Discussed by George F. Kay.

LICKS AND CAVES OF THE LOWER OHIO VALLEY AS REPOSITORIES OF MAMMALIAN REMAINS, INCLUDING THOSE OF MAN¹

BY ARTHUR M. MILLER

Upward of a century ago interest in mammalian remains entombed in the licks and caves of the Lower Ohio Valley was much more pronounced than it has been in recent years.

¹ Manuscript received by the Secretary of the Society in December, 1921.

Excavating at Big Bone Lick for such remains, mainly those of the mastodon, was a favorite pastime for such prominent personages as General William Henry Harrison (1795), Doctor Goforth, of Cincinnati (1804), President Thomas Jefferson (1807), and John Clifford, of Lexington, Kentucky (1816-1817).

What became of the Harrison Collection, consisting of thirteen hogsheads of bones and teeth, shipped by river to Pittsburgh, is not known. The Goforth Collection, which included a four-horse-wagon load of teeth, entrusted to the notorious Thomas Ashe for exhibit in England, soon after its arrival there was sold and its proceeds appropriated by the latter. The bulk of this collection is now in the Royal College of Surgeons in London. The Jefferson Collection was divided by him into three portions. One of these he presented to the American Philosophical Society of Philadelphia, another to the National Institute of France, and the remaining third he reserved for his own private collection. What became of the latter is not known. The Clifford Collection, at the death of the owner, in 1820, became by purchase the property of the Academy of Science in Philadelphia.

Successful excavations at the lick were carried on by other parties from time to time, the latest being by Prof. Nathaniel Shaler in 1869. A remarkable quantity of bones and teeth of various mammals, living and extinct, were obtained as the result of all these excavations, those belonging to the mastodon and mammoth alone being estimated by Mr. William Cooper in 1840 to have represented in individuals one hundred of the former and twenty of the latter. There is no indication, however, that the supply of these remains at Big Bone Lick had approached exhaustion when interest in them languished and excavating for them ceased.

Little effort was ever made to find these remains at other licks in the Ohio Valley, the only one having come to the notice of the writer being that of a Mr. Hunter, who in recent years has obtained a fine collection from the Lower Blue Lick in Nicholas County, Kentucky.

The caves known in the early day as the result of the development of the saltpeter industry also came in for their share of attention as repositories of these remains.

In 1805 Dr. Samuel Brown, of Lexington, referred to in the Medical and Physical Journal of Philadelphia for December of that year as "the very respectable and ingenious Dr. Samuel Brown," presented to the Academy of Science of Philadelphia the skull of what was at first supposed to be that of a "sus" or "hog," but was later by Dr. Joseph Leidy identified as that of an extinct peccary. This skull was obtained from a saltpeter cave on Crooked Creek, in what was then Madison, but is now Rockcastle, County, Kentucky.

John Clifford, about the same time, or perhaps a little later, obtained some megalonyx bones from a cave in White County, Tennessee, which after his death went with the rest of his collection to become the property of the Academy of Science of Philadelphia.

In 1814 there was found, either in Mammoth Cave or a neighboring cavern, an Indian mummy, which was described in volume 18 of the Medical Repository for that year. Its description was accompanied by a drawing made by C. S. Rafinesque; also, about the same time, various articles of aboriginal

manufacture, such as moccasins, bowls, etcetera, were found in Mammoth and neighboring caves, all as the result of the excavation of nitrous earth for saltpeter manufacture.

With the decadence of the saltpeter industry, soon after the War of 1812, excavating for nitrous earth practically ceased. The result of this was that for a long period we hear little of animal remains being found in caves. More recently, in consequence of lead and zinc mining operations in Scott County, Kentucky, a tapir's remains, apparently Pleistocene in age, were found in a filled-up sink-hole; and calcite mining on the Kentucky River, in Mercer County, disclosed traces of an extinct horse and deer in "mud pipes," which there vertically traverse the vein operated. These "mud pipes," which contain old river deposits, were formed by filling from above of solution channels in the calcite. The material in these "mud pipes" is identical in character with that of the old floodplain deposits of the Kentucky River, which were laid down before the river had cut its present gorge and are Pleistocene or Pliocene in age.

In the summer and fall of 1916 Dr. N. C. Nelson, of the American Museum of Natural History, fresh from the exploration of the caves of France and Spain, came to Kentucky to give it a "once over" as a field for archeological investigation. He left with a goodly collection of archeological material excavated at the entrance of Mammoth Cave.

Prompted by the opinion of Dr. Nelson that the caves of Kentucky, being similarly situated with reference to the southern margin of the glacial drift as those of France, should offer as good a field as the French caves for the discovery of evidence of glacial man, provided that human existence in this country dated that far back, the author of this paper has since 1916 been on the lookout for caves and rock shelters favorable for exploration with a view to obtaining such evidence.

The results thus far obtained are encouraging. Personal examination and the results of others making similar investigations prove the existence in Kentucky, and doubtless also in adjacent portions of Indiana and Tennessee, of a very large number of caves and rock shelters which contain archeological material, some of which, at least, is in association with remains of animals now extinct in the region.

In particular, as the result of investigations carried on during the past summer, do the caves and sinks in north-central Kentucky offer a favorable field for paleontological and archeological exploration. Two of these caves discovered during the past summer—the Breck Smith Cave, 8 miles west of Lexington, first explored by three young women, and an extension to the Phelps Cave, 4 miles southwest of the city, first entered by a lad of fifteen, resident of the farm on which it is situated—have yielded to excavations carried on by the writer and some of his colleagues a considerable number of bones. Thus far only the surface material has been removed. The remains identified from the Breck Smith Cave belong to the raccoon, ground-hog, gray fox, deer, wolf, buffalo, bear, and man (Indian); also a bone awl. All of these belong to existing species and do not indicate a high degree of antiquity for the fauna, with possibly the exception of the part identified as belonging to a bear, supposed by one of the authorities to whom it was submitted to indicate a polar bear.

In the extension to the Phelps Cave were found the remains of a black bear. These have a decidedly ancient appearance, being in some instances cemented together with stalagmitic material, and have been considerably altered. They are probably Pleistocene in age.

The conclusions drawn from the results of our own and the examinations of others are that there exist in the licks and caves of the Lower Ohio Valley an enormous number of bones of land animals, some of them going back to the Pleistocene, and with the more recent of these that are found in caves there are certainly associated human remains in considerable numbers.

The remains of the lower animals belong chiefly to those which either perished from being trapped in sinks or to those which were dragged into caves by predaceous animals. In some instances they belong to those animals which harbored in caves. The human remains are mainly of those people who sought shelter at the entrances or who were buried there or in the more remote recesses by their fellows.

Presented by title in the absence of the author.

CORRELATION OF THE JURASSIC FORMATIONS OF WESTERN CUBA

BY BARNUM BROWN AND MARJORIE O'CONNELL

(Abstract)

This paper presents the results of observations made by Mr. Brown during five journeys to Cuba covering eleven months of field-work and exploration in those provinces west of Camaguey and of three years of laboratory study of his collections of rocks and fossils by Miss O'Connell. The presence of the Oxfordian, Lusitanian, Kimmeridgian, and Portlandian divisions of the Jurassic has been established by the fossil faunas, and the correlation of the Cuban formations with synchronous ones in Europe and Mexico has been effected. A large ammonite fauna, including many new species, has been described and accurate intercontinental correlations have been made possible by the recognition in Cuba of the same faunal zones as were established by Oppel, Quenstedt, and later workers in the Swiss and Swabian Jura and southern France. The physiography, field relations, palatogeography, and correlations are shown in diagrams and maps.

Presented by the junior author in abstract from notes. Lantern slides were used in illustration.

Discussed by A. C. Lane, T. Wayland Vaughan, and Charles Schuchert.

DISCUSSION

Dr. VAUGHAN said that the Upper Cretaceous and Tertiary marine faunas of Central America and the West Indies find their European analogues in southern, not northern, Europe.

Dr. SCHUCHERT: It is interesting to note how each new discovery of Mesozoic marine faunas in the Antillean and Central American regions is more or less decidedly in harmony with southern European ones. As we are here dealing with shallow-water faunas, they fall in line with the previous ones,

which goes to show that there was a shallow-water sea and a shoreline across the Atlantic from Brazil to Africa. The speaker congratulates Doctor O'Connell on her good results.

The section adjourned at 5.20 o'clock p. m.

REGISTER OF THE AMHERST MEETING, 1921

FELLOWS

FRANK D. ADAMS	A. F. FOERSTE
R. C. ALLEN	W. G. FOYE
ROBERT ANDERSON	J. W. GOLDTHWAITE
GEORGE W. ASHLEY	C. E. GORDON
MANLEY B. BAKER	L. C. GRATON
FLORENCE BASCOM	A. O. HAYES
R. S. BASSLER	K. C. HEALD
E. S. BASTIN	N. E. A. HINDS
A. M. BATEMAN	R. J. HOLDEN
E. BLACKWELDER	E. O. HOVEY
N. L. BOWEN	E. HOWE
WILLIAM BOWIE	J. E. HYDE
E. B. BRANSON	E. C. JACOBS
T. C. BROWN	E. C. JEFFREY
W. H. BUCHER	D. W. JOHNSON
G. H. CHADWICK	R. H. JOHNSON
J. M. CLARKE	G. F. KAY
H. F. CLELAND	A. KEITH
J. A. CUSHMAN	J. F. KEMP
N. C. DALE	A. KNOPF
W. M. DAVIS	ELEANORA BLISS KNOPF
A. L. DAY	E. H. KRAUS
E. DE GOLYER	H. B. KÜMMEL
F. W. DE WOLF	A. C. LANE
J. S. DILLER	J. H. LEES
J. A. DRESSER	F. LEVERETT
C. O. DUNBAR	M. M. LEIGHTON
A. S. EAKLE	W. LINDGREN
B. K. EMERSON	F. B. LOOMIS
A. E. FATH	G. D. LOUDERBACK
C. N. FENNER	G. F. LOUGHLIN
H. G. FERGUSON	R. S. LULL

K. F. MATHER	J. E. SPURR
E. B. MATHEWS	G. O. SMITH
W. D. MATTHEW	W. S. SMITH
O. E. MEINZER	T. W. STANTON
B. L. MILLER	R. W. STONE
W. J. MILLER	G. W. STOSE
W. A. NELSON	M. TALBOT
D. H. NEWLAND	J. L. TILTON
MARJORIE O'CONNELL	E. O. ULRICH
J. A. OGILVIE	F. R. VAN HORN
S. PAIGE	T. W. VAUGHAN
R. A. F. PENROSE, JR.	A. C. VEATCH
G. H. PERKINS	T. C. WALKER
W. C. PHALEN	H. S. WASHINGTON
A. H. PHILLIPS	T. L. WATSON
P. E. RAYMOND	L. G. WESTGATE
C. A. REEDS	G. R. WIELAND
H. F. REID	F. A. WILDER
W. N. RICE	A. W. WILSON
H. RIES	E. T. WHERRY
A. F. ROGERS	DAVID WHITE
R. W. SAYLES	I. C. WHITE
C. SCHUCHERT	H. P. WHITLOCK
W. J. SINCLAIR	J. E. WOLFF
E. W. SHAW	J. B. WOODWORTH

FELLOWS-ELECT

WINIFRED GOLDRING	RAYMOND C. MOORE
OLIVER P. HAY	J. B. REESIDE
MORRIS M. LEIGHTON	

Besides these, there were registered 106 members of the affiliated societies and invited guests.

CONSTITUTION AND BY-LAWS

REFERENCES TO ADOPTION AND CHANGES

The provisional Constitution under which the Society was organized was approved August 15, 1888, and adopted December 27, 1888 (see Bulletin, volume 1, pages 7-8). These rules were elaborated and the revised Constitution and By-Laws were adopted December 27, 1889 (volume 1, pages 536, 571-578).

Several changes have been made in these rules, which are on record in the Bulletin as follows: Changes in the Constitution: December, 1894, volume 6, page 432; December, 1897, volume 9, page 400; December, 1909, volume 21, page 19. Changes in the By-Laws: December, 1891, volume 3, page 470; December, 1893, volume 5, pages 553-554; December, 1894, volume 6, page 432; December, 1903, volume 14, page 535; December, 1909, volume 21, page 19; December, 1920, volume 32, page 13.

CONSTITUTION

ARTICLE I

NAME

This Society shall be known as THE GEOLOGICAL SOCIETY OF AMERICA.

ARTICLE II

OBJECT

The object of this Society shall be the promotion of the Science of Geology in North America.

ARTICLE III

MEMBERSHIP

The Society shall be composed of Fellows, Correspondents, and Patrons.

1. Fellows shall be persons who are engaged in geological work or in teaching geology.

Fellows admitted without election under the provisional Constitution shall be designated as Original Fellows on all lists or catalogues of the Society.

2. Correspondents shall be persons distinguished for their attainments in Geological Science and not resident in North America.

3. Patrons shall be persons who have bestowed important favors upon the Society.

4. Fellows alone shall be entitled to vote or hold office in the Society.

ARTICLE IV

OFFICERS

1. The officers of the Society shall consist of a President, a First Vice-President, a Second Vice-President, and one Vice-President to represent each of the

societies affiliated with this Society, a Secretary, a Treasurer, an Editor, and six Councilors.

These officers, together with the Presidents for the next preceding three years, shall constitute an Executive Committee, which shall be called the Council.

2. The President shall discharge the usual duties of a presiding officer at all meetings of the Society and of the Council. He shall take cognizance of the acts of the Society and of its officers, and cause the provisions of the Constitution and By-Laws to be faithfully carried into effect.

3. The First Vice-President shall assume the duties of President in case of the absence or disability of the latter. The Second Vice-President shall assume the duties of President in case of the absence or disability of both the President and First Vice-President. The Third Vice-President shall assume the duties of President in case of the absence or disability of the President and the First and Second Vice-Presidents.

4. The Secretary shall keep the records of the proceedings of the Society, and a complete list of the Fellows, with the dates of their election and disconnection with the Society. He shall also be the secretary of the Council.

The Secretary shall cooperate with the President in attention to the ordinary affairs of the Society. He shall attend to the preparation, printing and mailing of circulars, blanks and notifications of elections and meetings. He shall superintend other printing ordered by the Society or by the President, and shall have charge of its distribution, under the direction of the Council.

The Secretary, unless other provision be made, shall also act as Editor of the publications of the Society, and as Librarian and Custodian of the property.

5. The Treasurer shall have the custody of all funds of the Society. He shall keep account of receipts and disbursements in detail, and this shall be audited as hereinafter provided.

6. The Editor shall supervise all matters connected with the publication of the transactions of the Society under the direction of the Council.

7. The Council is clothed with executive authority and with the legislative powers of the Society in the intervals between its meetings; but no extraordinary act of the Council shall remain in force beyond the next following stated meeting without ratification by the Society. The Council shall have control of the publications of the Society, under provisions of the By-Laws and of resolutions from time to time adopted. They shall receive nominations for Fellows, and, on approval by them, shall submit such nominations to the Society for action. They shall have power to fill vacancies *ad interim* in any of the offices of the Society.

8. *Terms of office.*—The President and Vice-Presidents shall be elected annually, and shall not be eligible to re-election more than once until after an interval of three years after retiring from office.

The Secretary, Treasurer, and Editor shall be eligible to re-election without limitation.

The term of office of the Councilors shall be three years; and these officers shall be so grouped that two shall be elected and two retire each year. Councilors retired shall not be re-eligible till after the expiration of a year.

ARTICLE V

VOTING AND ELECTIONS

1. All elections shall be by ballot. To elect a Fellow, Correspondent or Patron, or impose any special tax, shall require the assent of nine-tenths of all Fellows voting.

2. Voting by letter may be allowed.

3. *Election of Fellows.*—Nominations for fellowship may be made by two Fellows according to a form to be provided by the Council. One of these Fellows must be personally acquainted with the nominee and his qualifications for membership. The Council will submit the nominations received by them, if approved, to a vote of the Society in the manner provided in the By-Laws. The result may be announced at any stated meeting; after which notice shall be sent out to Fellows elect.

4. *Election of officers.*—Nominations for office shall be made by the Council. The nominations shall be submitted to a vote of the Society in the same manner as nominations for fellowship. The results shall be announced at the Annual Meeting; and the officers thus elected shall enter upon duty at the adjournment of the meeting.

ARTICLE VI

MEETINGS

1. The Society shall hold at least one stated meeting a year, in the winter season. The date and place of the Winter Meeting shall be fixed by the Council, and announced each year within three months after the adjournment of the preceding Winter Meeting. The program of each meeting shall be determined by the Council, and announced beforehand, in its general features. The details of the daily sessions shall also be arranged by the Council.

2. The Winter Meeting shall be regarded as the Annual Meeting. At this, elections of officers shall be declared, and the officers elect shall enter upon duty at the adjournment of the meeting.

3. Special meetings may be called by the Council, and must be called upon the written request of twenty Fellows.

4. Stated meetings of the Council shall be held coincidently with the stated meetings of the Society. Special meetings may be called by the President at such times as he may deem necessary.

5. *Quorum.*—At meetings of the Society a majority of those registered in attendance shall constitute a quorum. Five shall constitute a quorum of the Council.

ARTICLE VII

PUBLICATION

The serial publications of the Society shall be under the immediate control of the Council.

ARTICLE VIII

SECTIONS

Any group of Fellows representing a particular branch of geology may, with consent of the Council, organize as a section of the Society with separate con-

stitution and by-laws, provided that nothing in such constitution and by-laws conflict with the Constitution and By-Laws of the Geological Society of America, in letter or spirit, and provided that such constitution and by-laws and all amendments thereto shall have been approved by the Council.

ARTICLE IX

AMENDMENTS

1. This Constitution may be amended at any annual meeting by a three-fourths vote of all the Fellows, provided that the proposed amendment shall have been submitted in print to all Fellows at least three months previous to the meeting.

2. By-laws may be made or amended by a majority vote of the Fellows present and voting at any annual meeting, provided that printed notice of the proposed amendment or by-law shall have been given to all Fellows at least three months before the meeting.

BY-LAWS

CHAPTER I

OF MEMBERSHIP

1. No person shall be accepted as a Fellow unless he pay his initiation fee, and the dues for the year, within three months after notification of his election. The initiation fee shall be ten (10) dollars and the annual dues ten (10) dollars, the latter payable on or before the annual meeting in advance; but a single prepayment of one hundred fifty (150) dollars shall be accepted as commutation for life. A Fellow in good standing, however, who has paid annual dues for not less than fifteen (15) years may commute further dues and become a Life Fellow by making a single payment of one hundred (100) dollars.

2. The sums paid in commutation of dues shall be covered into the Publication Fund.

3. An arrearage in payment of annual dues shall deprive a Fellow of the privilege of taking part in the management of the Society and of receiving the publications of the Society. An arrearage continuing over two (2) years shall be construed as notification of withdrawal.

4. Any person eligible under Article III of the Constitution may be elected Patron upon the payment of one thousand (1,000) dollars to the Publication Fund of the Society.

CHAPTER II

OF OFFICIALS

1. The President shall countersign, if he approves, all duly authorized accounts and orders drawn on the Treasurer for the disbursement of money.

2. The Secretary, until otherwise ordered by the Society, shall perform the duties of Editor, Librarian, and Custodian of the property of the Society.

3. The Society may elect an Assistant Secretary.

4. The Treasurer shall give bonds, with two good sureties approved by the Council, in the sum of five thousand dollars, for the faithful and honest performance of his duties and the safe-keeping of the funds of the Society. He may deposit the funds in bank at his discretion, but shall not invest them without authority of the Council. His accounts shall be balanced as on the thirtieth day of November of each year.

5. In the selection of Councilors the various sections of North America shall be represented as far as practicable.

6. The minutes of the proceedings of the Council shall be subject to call by the Society.

7. The Council may transact its business by correspondence during the intervals between its stated meetings; but affirmative action by a majority of the Council shall be necessary in order to make action by correspondence valid.

CHAPTER III

OF ELECTION OF MEMBERS

1. Nominations for fellowship may be proposed at any time on blanks to be supplied by the Secretary.

2. The *form* for the nomination of Fellows shall be as follows:

In accordance with his desire, we respectfully nominate for Fellow of the Geological Society of America:

Full name; degrees; address; occupation; branch of Geology now engaged in, work already done and publications made.

(Signed by at least two Fellows.)

The form when filled is to be transmitted to the Secretary.

3. The Secretary will bring all nominations before the Council, and the Council will signify its approval or disapproval of each.

4. At least a month before one of the stated meetings of the Society the Secretary will mail a printed list of all approved nominees to each Fellow, accompanied by such information as may be necessary for intelligent voting; but an informal list of the candidates shall be sent to each Fellow at least two weeks prior to distribution of the ballots.

5. The Fellows receiving the list will signify their approval or disapproval of each nominee, and return the lists to the Secretary.

6. At the next stated meeting of the Council the Secretary will present the lists and the Council will canvass the returns.

7. The Council, by unanimous vote of the members in attendance, may still exercise the power of rejection of any nominee whom new information shows to be unsuitable for fellowship.

8. At the next stated meeting of the Society the Council shall declare the results.

9. Correspondents and Patrons shall be nominated by the Council, and shall be elected in the same manner as Fellows.

CHAPTER IV

OF ELECTION OF OFFICERS

1. The Council shall prepare a list of nominations for the several offices, which list will constitute the regular ticket. The ticket must be approved by a majority of the entire Council. The nominee for President shall not be a member of the Council. The nominee for Third Vice-President shall be the nominee for the presidency of the Paleontological Society, which has been organized as a section under Article VIII of the Constitution. The nominee for the Vice-President representing an affiliated society shall be from the joint fellowship by vote of the affiliated society concerned, subject to confirmation by the Council of the Geological Society of America.

2. The list shall be mailed to the Fellows, for their information, at least nine months before the Annual Meeting. Any five Fellows may forward to the Secretary other nominations for any or all offices. All such nominations reaching the Secretary at least 40 days before the Annual Meeting shall be printed, together with the names of the nominators, as special tickets. The regular and special tickets shall then be mailed to the Fellows at least 25 days before the Annual Meeting.

3. The Fellows will send their ballots to the Secretary in double envelopes, the outer envelope bearing the voter's name. At the Winter Meeting of the Council, the Secretary will bring the returns of ballots before the Council for canvass, and during the Winter Meeting of the Society the Council shall declare the result.

4. In case a majority of all the ballots shall not have been cast for any candidate for any office, the Society shall by ballot at such Winter Meeting proceed to make an election for such office from the two candidates having the highest number of votes.

CHAPTER V

OF FINANCIAL METHODS

1. No pecuniary obligation shall be contracted without express sanction of the Society or the Council. But it is to be understood that all ordinary, incidental, and running expenses have the permanent sanction of the Society, without special action.

2. The creditor of the Society must present to the Treasurer a fully itemized bill, certified by the official ordering it, and approved by the President. The Treasurer shall then pay the amount out of any funds not otherwise appropriated, and the receipted bill shall be held as his voucher.

3. At each annual meeting, the President shall call upon the Society to choose two Fellows, not members of the Council, to whom shall be referred the books of the Treasurer, duly posted and balanced to the close of November thirtieth, as specified in the By-Laws, Chapter II, clause 4. The Auditors shall examine the accounts and vouchers of the Treasurer, and any member or members of the Council may be present during the examination. The report of the Auditors shall be rendered to the Society before the adjournment of the meeting, and the Society shall take appropriate action.

CHAPTER VI

OF PUBLICATIONS

1. The publications are in charge of the Council and under its control.
2. One copy of each publication shall be sent to each Fellow, Correspondent, and Patron, and each author shall receive forty (40) copies of his memoir.

CHAPTER VII

OF THE PUBLICATION FUND

1. The Publication Fund shall consist of donations made in aid of publication, and of the sums paid in commutation of dues, according to the By-Laws, Chapter I, clause 2.
2. Donors to this fund, not Fellows of the Society, in the sum of two hundred dollars, shall be entitled, without charge, to the publications subsequently appearing.

CHAPTER VIII

OF ORDER OF BUSINESS

1. The Order of Business at Winter Meetings shall be as follows:
 - (1) Call to order by the presiding officer.
 - (2) Introductory ceremonies.
 - (3) Report of the Council (including report of the officers).
 - (4) Appointment of the Auditing Committee.
 - (5) Declaration of the vote for officers, and election by the meeting in case of failure to elect by the Society through transmitted ballots.
 - (6) Declaration of the vote for Fellows.
 - (7) Deferred business.
 - (8) New business.
 - (9) Announcements.
 - (10) Necrology.
 - (11) Reading of scientific papers.
2. At an adjourned session the order shall be resumed at the place reached on the previous adjournment, but new business will be in order before the reading of scientific papers.
3. At the Summer Meeting the items of business under numbers (3), (4), (5), (10) shall be omitted.
4. At any Special Meeting the order of business shall be numbers (1), (2), (3), (9), followed by the special business for which the meeting was called.

PUBLICATION RULES OF THE GEOLOGICAL SOCIETY OF AMERICA

(Adopted by the Council April 21, 1891; Revised April 30, 1894, May, 1904, and February 5, 1910)

GENERAL PROVISIONS

SECTION 1. The Council shall annually appoint from their own number a Publication Committee, consisting of the Secretary, the Treasurer, the Editor, and two others, whose duties shall be to determine the disposition of matter offered for publication, except as provided in section 12; to determine the expediency, in view of the financial condition of the Society, of publishing any matter accepted on its merits; to exercise general oversight of the matter and manner of publication; to determine the share of the cost of publication (including illustrations) to be borne by the author when it becomes necessary to divide cost between the Society and the author; to adjudicate any questions relating to publication that may be raised from time to time by the Editor or by the Fellows of the Society; and in general to act for the Council in all matters pertaining to publication. (Cons., Art. IV, 7; Art. VII; By-Laws, chap. VI.)

2. The duties of the Editor are to receive material offered for publication; to examine and submit it, with estimates of cost, to the Publication Committee; to publish all material accepted by the Council or Publication Committee; to revise proofs in connection with authors; to prepare lists of contents and general indexes; to audit bills for printing and illustrating; and to perform all other duties connected with publication not assigned to other officers. (Cons., Art. IV, 6; Rules, Sec. 16.)

3. The duties of the Secretary include the preparation of a record of the proceedings of each meeting of the Society in form for publication, and the custody, distribution, sale, exchange or other authorized disposition of the publications. (Cons., Art. IV, 4; By-Laws, chap. II, 2.)

4. Special committees may be appointed by the Council or the Publication Committee to examine and report on any matter offered for publication. (Rules, Sec. 11.)

THE BULLETIN

TITLE AND GENERAL CHARACTER

5. The Society shall publish a serial record of its work entitled "Bulletin of the Geological Society of America."

6. The Bulletin shall be published in quarterly parts, consecutively paged for each volume. The parts shall be suitably designated and each shall bear a title setting forth the contents and authorship, the seal and imprint of the Society and the date of publication.

7. The closing quarterly part of each volume shall contain an index, paged consecutively with the body of the volume; and it shall be accompanied by a volume title-page and lists of contents and illustrations, together with lists of

the publications of the Society and such other matter as the Publication Committee may deem necessary, all arranged under Roman pagination.

MATTER OF THE BULLETIN

8. The matter published in the Bulletin shall comprise (1) communications presented at meetings by title or otherwise; (2) communications or memoirs not presented before the Society; (3) abstracts of papers read before the Society, prepared or revised for publication by authors; (4) reports of discussions held before the Society, prepared or revised for publication by authors; (5) proceedings of the meetings of the Society prepared by the Secretary; (6) plates, maps, and other illustrations necessary for the proper understanding of communications; (7) lists of Officers and Fellows, Constitution, By-Laws, resolutions of permanent character, rules relating to procedure, to publication, and to other matters, etcetera, and (8) indexes, title-pages, and lists of contents for each volume.

9. Abstracts, reports of discussion, or other matter purporting to emanate from any author shall not be published unless prepared or revised by the author.

10. Manuscript designed for publication in the Bulletin must be complete as to copy for text and illustration, except by special arrangement between the author and the Council or Publication Committee; it must be perfectly legible (preferably typewritten) and preceded by a table of contents (section 15). The cost of necessary revision of copy or reconstruction of illustrations shall be assessed on the author.

11. The Editor shall examine matter designated for publication, and shall prepare an itemized estimate of the cost of publication and convey the whole to the Publication Committee. The Publication Committee shall then scrutinize the communication with reference, first, to relevancy; second, to scientific value; third, to literary character, and, fourth, to cost of publication, including revision. For advice with reference to the relevancy, scientific value, and literary character of any communication the Publication Committee may refer it to a special committee of their own number or of the Society at large or may call to their aid from outside one or more experts. Questions of disagreement between the Editor and authors shall be referred to the Publication Committee and appeal may be taken to the Council.

12. Communications from non-fellows shall be published only by specific authority from the Council.

13. Communications from Fellows not presented at regular meetings of the Society shall be published only upon unanimous vote of the Publication Committee, except by specific authority from the Council.

14. Matter offered for publication becomes thereby the property of the Society, and shall not be published elsewhere prior to publication in the Bulletin, except by consent of the Publication Committee.

DETAILS OF THE BULLETIN

15. The matter of each memoir shall be classified by subjects, and the classification suitably indicated by subtitles; and a list of contents shall be ar-

ranged; and such memoir may, at the option of the Publication Committee, contain an alphabetical index, provided the author prepare and pay for it.

16. Proofs of text and illustrations shall be submitted to authors whenever practicable; but printing shall not be delayed by reason of absence or incapacity of authors more than one week beyond the time required for transmission by mail. Complete proofs of the proceedings of meetings shall be sent to the Secretary, and proofs of papers and abstracts contained therein and exceeding one-half page in length shall be sent also to authors.

17. The cost of proof corrections in excess of ten per cent on the cost of printing may be charged to authors.

18. Unless the author of a memoir objects thereto, the discussion upon his communication shall be printed at the end thereof, with a suitable reference in the list of contents. In case the author objects to this arrangement, the discussion shall be printed in the closing number of the volume.

19. The author of each memoir occupying four pages or more of text in the body of the Bulletin shall receive 40 "separates" without charge, and may order through the Editor any edition of exactly similar separates at an advance of ten per cent on the cost of paper, presswork and binding; and no author's separates of such memoirs shall be issued except in this regular form.

20. Authors of papers, abstracts, or discussions less than four printed pages in length may order, through the Editor, at an advance of ten per cent on the cost of paper, presswork, binding and necessary composition, any number of extra copies, provided they bear the original pagination and a printed reference to the serial and volume from which they are extracted.

21. The Editor shall keep a record of all publications issued wholly or in part under the auspices of the Society, whether they be author's editions of memoirs, author's extracts from proceedings, or any other matter printed from type originally composed for the Bulletin.

DIRECTIONS TO PRINTER

22. Each memoir of the Bulletin shall begin, under its proper title, on an odd-numbered page bearing at its head the title of the serial, the volume number, the part number, the limiting pages, the plates, and the date of publication, together with a list of contents. Each memoir shall be accompanied by the illustrations pertaining to it, the plates numbered consecutively for the volume.

23. The author's separates of each memoir shall be enclosed in a cover bearing at the head of its title-page the title of the serial, the volume number, the limiting pages, and the numbers of the contained plates; in its upper-central part a title indicating the contents and authorship; in its lower-central part the seal of the Society; and at the bottom the imprint of the Society. (See also sections 19 and 20.)

24. The bottom of each signature and each initial page will bear a signature mark giving an abbreviated title of the serial, the volume, and the year; and every page (except volume title-page) shall be numbered, the initial and subtitle pages in parentheses at bottom.

25. The page-head titles shall be: on even-numbered pages, name of author and catch title of paper; on odd-numbered pages, catch title to contents of page.

26. The date of publication of each brochure shall be the day upon which the last form is locked and put on the press.

27. The type used in printing the Bulletin shall be as follows: For memoirs, body, long primer, 6-to-pica leads; extracts, brevier, 8-to-pica leads; footnotes, nonpareil, set solid; titles, long primer caps, with small caps for author's name; subtitles, long primer caps, small caps, italic, etcetera, as far as practicable; for designation of cuts, nonpareil caps and italics, and for legends, nonpareil, Roman, set solid; for lists of contents of brochures, brevier, 6-to-pica leads, a new line to an entry, running indentation; for volumes, the same, except 4-to-pica leads and names of authors in small caps; for indexes, nonpareil, set solid, double column, leaders, catch words in small caps, with spaces between initial letters. For serial titles, on initial pages, brevier block caps, with corresponding small caps for volume designation, etcetera; on covers, the same, except for page heads long primer caps; for serial designation, long primer; for brochure designation, pica caps; special title and author's name, etcetera, long primer and brevier caps; no frame on cover. No change in type shall be made to adjust matter to pages.

28. Volumes, plates, and cuts in text shall be numbered in Arabic; Roman numeration shall be used only in signature marks, and in paging the lists of contents, etcetera, arranged for binding at the beginning of the volume.

29. Imprimatur of Editor, on volume title-page; imprimatur of Council and Publication Committee, on obverse of volume title-page; imprimatur of Secretary, on initial pages and covers of brochures of proceedings. Printer's card, in fine type on obverse of title-page.

30. The paper shall be for body of volume, 70-pound toned paper, folding to 16 x 25 centimeters; for plates, good quality plate paper, smooth-surfaced, white, cut to 6½ x 10 inches for single plates; for covers smooth-surfaced, fine quality 70-pound light-buff manila paper.

31. The sheets of the brochures shall be stitched with thread; single page plates shall be stitched with the sheets of the brochure; folding plates may be either gummed or stitched (mounted on stubs if necessary); covers shall be gummed.

EDITION, DISTRIBUTION, AND PRICE

32. The regular edition shall be 750 copies in the regular quarterly form and 50 copies separately in covers of each memoir occupying four pages or more of text. Each author of a memoir occupying not less than four pages of text shall receive 40 copies of his memoir gratis. If two or more authors contribute to a memoir brochure of four pages or more in length, the edition shall be enlarged so as to give each author 40 copies. (By-Laws, chap. VI, 2.)

33. The undistributed residue of separates shall be held for sale.

34. The Bulletin shall be sent free to Fellows of the Society not in arrears for dues, and also to exchanging institutions. (By-Laws, chap. I, 3.)

35. The price of the Bulletin shall be as follows: To Fellows, libraries, and institutions, and to individuals not residing in North America, \$9.00 per volume; to individuals residing in North America and who are not Fellows, \$10. The price of each brochure shall be a multiple of five cents, and shall be, to Fellows, one cent per page plus three cents per plate, and to the public an advance of fifty per cent on the price to Fellows. The prices of the separate brochures and of the quarterly parts may be found in the front of each volume.

OFFICERS, CORRESPONDENTS, AND FELLOWS OF THE
GEOLOGICAL SOCIETY OF AMERICA

OFFICERS FOR 1922

President:

CHARLES SCHUCHERT, New Haven, Conn.

Vice-Presidents:

HENRY S. WASHINGTON, Washington, D. C.

ROBERT T. HILL, Glendale, Calif.

W. D. MATTHEW, New York City

T. L. WALKER, Toronto, Canada

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History,
New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1922)

T. W. VAUGHAN, Washington, D. C.

GEORGE F. KAY, Iowa City, Iowa

(Term expires 1923)

L. C. GRATON, Cambridge, Mass.

G. D. LOUDERBACK, Berkeley, Calif.

(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio

*MEMBERSHIP, 1921**CORRESPONDENTS*

- BARROIS, CHARLES, Lille, France. December, 1909.
 BRÖGGER, W. C., Christiania, Norway. December, 1909.
 CAPELLINI, GIOVANNI, Bologna, Italy. December, 1910.
 DE GEER, BARON GERHARD, Stockholm, Sweden. December, 1910.
 DE MARGERIE, EMMANUEL, Strasbourg, Alsace, France. December, 1921.
 GEIKIE, SIR ARCHIBALD, Hasslemeré, England. December, 1909.
 HEIM, ALBERT, Zürich, Switzerland. December, 1909.
 KAYSER, EMANUEL, Marburg, Germany. December, 1909.
 KILIAN, W., Grenoble, France. December, 1912.
 TEALL, J. J. H., London, England. December, 1912.
 TIETZE, EMIL, Vienna, Austria. December, 1910.

FELLOWS

* Indicates Original Fellows (see article III of Constitution)

- ABBE, CLEVELAND, JR., 625 So. Broadway, Yonkers, N. Y. August, 1899.
 ADAMS, FRANK DAWSON, McGill University, Montreal, Canada. Dec., 1889.
 ADAMS, GEORGE I., University of Alabama, Tuscaloosa, Ala. December, 1902.
 ADKINS, WALTER S., Apartado 150, Tampico, Tamaulipas, Mexico. Dec., 1921.
 ALCOCK, F. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
 ALDEN, WILLIAM C., U. S. Geological Survey, Washington, D. C. Dec., 1909.
 ALDRICH, TRUMAN H., 1026 Glen Iris Ave., Birmingham, Ala. May, 1889.
 ALLAN, JOHN A., University of Alberta, Strathcona, Canada. December, 1914.
 ALLEN, R. C., 1001 Kirby Building, Cleveland, Ohio. December, 1911.
 ALLING, H. L., University of Rochester, Rochester, N. Y. December, 1920.
 AMI, HENRY M., Strathcona Park, Ottawa, Canada. December, 1889.
 ANDERSON, FRANK M., State Mining Bureau, 2604 Aetna St., Berkeley, Calif. December, 1902.
 ANDERSON, ROBERT V., Menlo Park, Calif. December, 1911.
 ANDREWS, E. C., Geol. Surv. of N. S. W., Sydney, N. S. Wales. Dec., 1920.
 ARNOLD, RALPH, 639 South Spring St., Los Angeles, Calif. December, 1904.
 ASHLEY, GEORGE HALL, State Capitol, Harrisburg, Pa. August, 1895.
 ATWOOD, WALLACE WALTER, Clark University, Worcester, Mass. Dec., 1909.
 BAGG, RUFUS MATHER, JR., 7 Brokaw Place, Appleton, Wis. December, 1896.
 BAIN, H. FOSTER, 1430 33d St. N. W., Washington, D. C. December, 1895.
 BAKER, MANLEY BENSON, School of Mining, Kingston, Ontario. Dec., 1911.
 BALDWIN, S. PRENTISS, 2930 Prospect Ave., Cleveland, Ohio. August, 1895.
 BALL, SYDNEY H., 42 Broadway, New York City. December, 1905.
 BANCROFT, JOSEPH A., McGill University, Montreal, Canada. December, 1914.
 BARBOUR, ERWIN HINCKLEY, University of Nebraska, Lincoln, Neb. Dec., 1896.
 BARTON, DONALD C., Amerada Pet. Corp., Houston, Texas. December, 1921.
 BARTON, GEORGE H., Boston Society of Natural History, Boston, Mass. August, 1890.
 BARTSCH, PAUL, U. S. National Museum, Washington, D. C. December, 1917.
 BASCOM, FLORENCE, Bryn Mawr College, Bryn Mawr, Pa. August, 1894.

- BASSLER, RAY SMITH, U. S. National Museum, Washington, D. C. Dec., 1906.
BASTIN, EDSON S., University of Chicago, Chicago, Ill. December, 1909.
BATEMAN, ALAN MARA, Yale University, New Haven, Conn. December, 1916.
BAYLEY, WILLIAM S., University of Illinois, Urbana, Ill. December, 1888.
BEEDE, JOSHUA W., 404 West 38th St., Austin, Texas. December, 1902.
BENSON, W. N., University of Otago, Dunedin, New Zealand. Dec., 1919.
BERKEY, CHARLES P., Columbia University, New York, N. Y. August, 1901.
BERRY, EDWARD WILBER, Johns Hopkins University, Baltimore, Md. Dec., 1909.
BEYER, SAMUEL WALKER, Iowa Agricultural College, Ames, Iowa. Dec., 1896.
BLACKWELDER, ELIOT, 740 Olive St., Denver, Colo. December, 1908.
BOUTWELL, JOHN M., Nat. Copper Bank, Salt Lake City, Utah. Dec., 1905.
BOWEN, CHARLES F., c/o Standard Oil Co., 26 Broadway, New York City.
December, 1916.
BOWEN, N. L., Geophysical Laboratory, Washington, D. C. December, 1917.
BOWIE, WILLIAM, U. S. Coast and Geodetic Survey, Washington, D. C.
December, 1919.
BOWNOCKER, JOHN ADAMS, Ohio State University, Columbus, Ohio. Dec., 1904.
*BRANNER, JOHN C., Leland Stanford, Jr., University, Stanford Univ., Calif.
BRANSON, EDWIN BAYER, University of Missouri, Columbia, Mo. Dec., 1911.
BRETZ, J. H., University of Chicago, Chicago, Ill. December, 1917.
BRIGHAM, ALBERT PERRY, Colgate University, Hamilton, N. Y. December, 1893.
BROCK, REGINALD W., Univ. of British Columbia, Vancouver, B. C. Dec., 1904.
BRODERICK, T. MONTEITH, Calumet and Hecla Mining Co., Calumet, Mich.
December, 1921.
BROKAW, A. D., 157 Maplewood Ave., Maplewood, N. J. December, 1920.
BROOKS, ALFRED HULSE, U. S. Geological Survey, Washington, D. C. Aug., 1899.
BROWN, BARNUM, American Museum of Natural History, New York, N. Y.
December, 1910.
BROWN, CHARLES WILSON, Brown University, Providence, R. I. Dec., 1908.
BROWN, THOMAS CLACHAR, Laurel Bank Farm, Fitchburg, Mass. Dec., 1915.
BRUCE, E. L., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
BUCHER, W. H., University of Cincinnati, Cincinnati, Ohio. December, 1920.
BUDDINGTON, A. F., Brown University, Providence, R. I. December, 1919.
BUEHLER, HENRY ANDREW, Rolla, Mo. December, 1909.
BURCHARD, E. F., U. S. Geological Survey, Washington, D. C. December, 1920.
BURLING, LANCASTER D., Whitehall Petr. Corp., 53 Parliament St., Westminster, S. W. I., London, England. December, 1917.
BURWASH, EDWARD M. J., Victoria College, Toronto, Canada. December, 1916.
BUTLER, BERT S., Box 277, Calumet, Mich. December, 1912.
BUTLER, G. MONTAGUE, College of Mines, Tucson, Arizona. December, 1911.
BUTTS, CHARLES, U. S. Geological Survey, Washington, D. C. December, 1912.
BUWALDA, J. P., University of California, Berkeley, Calif. December, 1920.
CADY, G. H., Fayetteville, Ark. December, 1920.
CALHOUN, FRED HARVEY HALL, Clemson College, S. C. December, 1909.
CALKINS, FRANK C., U. S. Geological Survey, Washington, D. C. Dec., 1914.
CAMPBELL, HENRY D., Washington and Lee Univ., Lexington, Va. May, 1889.
CAMPBELL, MARIUS R., U. S. Geological Survey, Washington, D. C. Aug., 1892.
CAMPOS, LUIZ FILIPPE G. DE, Geological Survey of Brazil, Rio de Janeiro,
Brazil. December, 1917.

- CAMSELL, CHARLES, Department of Mines, Ottawa, Canada. December, 1914.
- CAPPS, STEPHEN R., JR., U. S. Geological Survey, Washington, D. C. Dec., 1911.
- CARMAN, J. ERNEST, Ohio State University, Columbus, Ohio. December, 1917.
- CARNEY, FRANK, 208 S. Chautauqua St., Wichita Kans. December, 1908.
- CASE, ERMINE C., University of Michigan, Ann Arbor, Mich. December, 1901.
- CHADWICK, GEORGE H., University of Rochester, Rochester, N. Y. Dec., 1911.
- CHAMBERLIN, ROLLIN T., University of Chicago, Chicago, Ill. December, 1913.
- *CHAMBERLIN, T. C., University of Chicago, Chicago, Ill.
- CLAGHORN, CLARENCE RAYMOND, 22 Dover Road, Wellesley, Mass. Aug., 1891.
- CLAPP, CHARLES H., State University, Missoula, Mont. December, 1914.
- CLAPP, FREDERICK G., 30 Church St., New York City. December, 1905.
- CLARK, BRUCE L., Bacon Hall, Univ. of California, Berkeley, Calif. Dec., 1918.
- CLARK, F. R., U. S. Geological Survey, Washington, D. C. December, 1919.
- CLARK, W. O., Pahala, Kau, Hawaii. December, 1920.
- CLARKE, JOHN MASON, Education Building, Albany, N. Y. December, 1897.
- CLELAND, HERDMAN F., Williams College, Williamstown, Mass. Dec., 1905.
- CLEMENTS, J. MORGAN, 20 Broad St., New York City. December, 1894.
- COBB, COLLIER, University of North Carolina, Chapel Hill, N. C. Dec., 1894.
- COLEMAN, ARTHUR P., Toronto University, Toronto, Canada. December, 1896.
- COLLIE, GEORGE L., Beloit College, Beloit, Wis. December, 1897.
- COLLINS, WILLIAM H., Geological Survey, Ottawa, Canada. December, 1921.
- COLLIER, ARTHUR J., U. S. Geological Survey, Washington, D. C. June, 1902.
- CONDIT, D. DALE, c/o S. Pearson & Son, 47 Parliament St., London, England. December, 1916.
- COOK, CHARLES W., University of Michigan, Ann Arbor, Mich. Dec., 1915.
- COOKE, C. WYTHE, U. S. Geological Survey, Washington, D. C. Dec., 1918.
- COSTE, EUGENE, 2208 Amherst St., Calgary, Alberta, Canada. Dec., 1906.
- COX, G. H., 625 State St., Pine Bluff, Ark. December, 1920.
- CRAWFORD, RALPH DIXON, 1050 Tenth St., Boulder, Colo. December, 1916.
- CROOK, ALJA R., State Museum of Natural History, Springfield, Ill. Dec., 1898.
- *CROSBY, WILLIAM O., Massachusetts Institute of Technology, Boston, Mass.
- CROSS, WHITMAN, 2138 Bancroft Place, Washington, D. C. May, 1889.
- CULVER, GARRY E., 310 Center Ave., Stevens Point, Wis. December, 1891.
- CUMINGS, EDGAR R., Indiana University, Bloomington, Ind. August, 1901.
- CUSHMAN, J. A., Sharon, Mass. December, 1919.
- DAKE, C. L., Missouri School of Mines, Rolla, Mo. December, 1920.
- DALE, N. C., Hamilton College, Clinton, N. Y. December, 1920.
- DALY, REGINALD A., Harvard University, Cambridge, Mass. December, 1905.
- DANA, EDWARD SALISBURY, Yale University, New Haven, Conn. Dec., 1908.
- *DARTON, NELSON H., U. S. Geological Survey, Washington, D. C.
- DAVIS, E. F., 343 Sansome St., San Francisco, Calif. December, 1920.
- *DAVIS, WILLIAM M., 31 Hawthorne St., Cambridge, Mass.
- DAY, ARTHUR LOUIS, Geophysical Laboratory, Washington, D. C. Dec., 1909.
- DAY, DAVID T., 1333 F St. N. W., Washington, D. C. August, 1891.
- DEAN, BASHFORD, Columbia University, New York, N. Y. December, 1910.
- DE GOLYER, E. L., 65 Broadway, New York City. December, 1918.
- DEUSSEN, ALEXANDER, 504 Stewart Bldg., Houston, Texas. December, 1916.
- DE WOLF, FRANK WILBRIDGE, Urbana, Ill. December, 1909.
- DICKERSON, ROY E., Masonic Temple Building, Manila, P. I. December, 1918.

- *DILLER, JOSEPH S., U. S. Geological Survey, Washington, D. C.
 D'INVILLIERS, EDWARD V., 518 Walnut St., Philadelphia, Pa. December, 1888.
 DODGE, RICHARD E., Dodge Farm, Washington, Conn. August, 1897.
 DRAKE, NOAH FIELDS, Fayetteville, Arkansas. December, 1898.
 DRESSER, JOHN A., 701 Eastern Townships Bank Bldg., Montreal, Canada.
 December, 1906.
 *DUMBLE, EDWIN T., 2003 Main St., Houston, Texas.
 DUNBAR, C. O., Yale University, New Haven, Conn. December, 1920.
 EAKLE, ARTHUR S., University of California, Berkeley, Calif. December, 1899.
 ECKEL, EDWIN C., Munsey Building, Washington, D. C. December, 1905.
 EMERY, WILSON B., Casper, Wyoming. December, 1919.
 *EMERSON, BENJAMIN K., Amherst, Mass.
 EMMONS, WILLIAM H., Univ. of Minnesota, Minneapolis, Minn. Dec., 1912.
 *FAIRCHILD, HERMAN L., University of Rochester, Rochester, N. Y.
 FARRINGTON, OLIVER C., Field Museum of Natural History, Chicago, Ill. De-
 cember, 1895.
 FATH, A. E., U. S. Geological Survey, Washington, D. C. December, 1920.
 FENNEMAN, NEVIN M., University of Cincinnati, Cincinnati, Ohio. Dec., 1904.
 FENNER, CLARENCE N., Geophysical Laboratory, Washington, D. C. Dec., 1911.
 FERGUSON, H. G., U. S. Geological Survey, Washington, D. C. December, 1920.
 FISHER, CASSIUS ASA, 705 First Natl. Bank Bldg., Denver, Colo. Dec., 1908.
 FOERSTE, AUGUST F., 129 Wroe Ave., Dayton, Ohio. December, 1899.
 FORD, WILLIAM E., Sheffield Scientific School, New Haven, Conn. Dec., 1915.
 FOYE, W. G., Wesleyan University, Middletown, Conn. December, 1919.
 FULLER, MYRON L., 157 Spring St., Brockton, Mass. December, 1898.
 GALLOWAY, J. J., Columbia University, New York, N. Y. December, 1920.
 GALPIN, SIDNEY L., 630 Park Ave., Ames, Iowa. December, 1917.
 GANE, HENRY STEWART, Rural Del. No. 1, Santa Barbara, Calif. Dec., 1896.
 GARDNER, JAMES H., 626 Kennedy Building, Tulsa, Okla. December, 1911.
 GARDNER, JULIA A., U. S. Geological Survey, Washington, D. C. Dec., 1920.
 GEORGE, RUSSELL D., University of Colorado, Boulder, Colo. December, 1906.
 GILES, ALBERT W., University of Virginia, University, Va. December, 1921.
 GILL, ADAM CAPEN, Cornell University, Ithaca, N. Y. December, 1888.
 GLENN, L. C., Vanderbilt University, Nashville, Tenn. June, 1900.
 GOLDMAN, MARCUS ISAAC, U. S. Geol. Survey, Washington, D. C. Dec., 1916.
 GOLDRING, WINIFRED, New York State Museum, Albany, N. Y. Dec., 1921.
 GOLDTHWAIT, JAMES WALTER, Dartmouth College, Hanover, N. H. Dec., 1909.
 GORDON, CHARLES H., University Library, University of Tennessee, Knoxville,
 Tenn. August, 1893.
 GORDON, CLARENCE E., Massachusetts Agricultural College, Amherst, Mass.
 December, 1913.
 GOULD, CHARLES N., 1218 Colcord Bldg., Oklahoma City, Okla. Dec., 1904.
 GRABAU, AMADEUS W., Government University, Pekin, China. Dec., 1898.
 GRANGER, WALTER, American Museum of Natural History, New York, N. Y.
 December, 1911.
 GRANT, ULYSSES SHERMAN, Northwestern Univ., Evanston, Ill. Dec., 1890.
 GRASTY, JOHN SHARSHALL, Box 458, Charlottesville, Va. December, 1911.
 GRATON, LOUIS C., Foxcroft House, Cambridge, 38, Mass. December, 1913.
 GREGORY, HERBERT E., Yale University, New Haven, Conn. August, 1901.

- GREENE, FRANK COOK, 30 North Yorktown St., Tulsa, Okla. December, 1917.
- GRIMSLEY, GEORGE P., 16 York Court, Baltimore, Md. August, 1895.
- GROUT, FRANK F., University of Minnesota, Minneapolis, Minn. Dec., 1918.
- GURLEY, WILLIAM F. E. R., University of Chicago, Chicago, Ill. Dec., 1914.
- HALBERSTADT, BAIRD, Pottsville, Pa. December, 1909.
- HANCE, J. H., 708 W. Washington Boulevard, Urbana, Ill. December, 1920.
- HANCOCK, E. T., U. S. Geological Survey, Washington, D. C. December, 1919.
- HARDER, E. C., 1111 Harrison Building, Philadelphia, Pa. December, 1918.
- HARES, C. J., the Ohio Oil Co., Casper, Wyo. December, 1920.
- HARRIS, GILBERT D., Cornell University, Ithaca, N. Y. December, 1903.
- HARRISON, JOHN BURCHMORE, Georgetown, British Guiana. June, 1902.
- HARTNAGEL, CHRIS A., Education Building, Albany, N. Y. December, 1913.
- HASTINGS, JOHN B., 5456 Sierra Vista Ave., Los Angeles, Calif. May, 1889.
- *HAWORTH, ERASMUS, University of Kansas, Lawrence, Kans.
- HAY, OLIVER P., Carnegie Institution, Washington, D. C. December, 1921.
- HAYES, ALBERT O., c/o Carr Bros., Inc., 65 Broadway, N. Y. City. Dec., 1919.
- HEALD, K. C., U. S. Geological Survey, Washington, D. C. December, 1920.
- HENNEN, RAY V., 1701 Benedum-Trees Bldg., Pittsburgh, Pa. December, 1914.
- HERSHEY, OSCAR H., Crocker Building, San Francisco, Calif. December, 1909.
- HESS, FRANK L., U. S. Geological Survey, Washington, D. C. December, 1921.
- HEWETT, DONNEL F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- HICE, RICHARD R., Beaver, Pa. December, 1903.
- HILL, J. M., U. S. Geological Survey, Washington, D. C. December, 1920.
- HILL, ROBERT T., 623 N. Central Ave., Glendale, Calif.
- HILLS, RICHARD C., Denver, Colo. August, 1894.
- HINDS, HENRY, 1153 Laurel Ave., St. Paul, Minn. December, 1912.
- HINTZE, FERDINAND FRIIS, 580 Corona St., Denver, Colo. December, 1917.
- HOBBS, WILLIAM H., University of Michigan, Ann Arbor, Mich. August, 1891.
- *HOLBROOK, LEVI, P. O. Box 536, New York, N. Y.
- HOLDEN, ROY J., Virginia Polytechnic Institute, Blacksburg, Va. Dec., 1914.
- HOLLAND, WILLIAM JACOB, Carnegie Museum, Pittsburgh, Pa. December, 1910.
- HOLLICK, ARTHUR, N. Y. Botanical Garden, New York, N. Y. August, 1898.
- HOPKINS, O. B., U. S. Geological Survey, Washington, D. C. December, 1919.
- HOPKINS, THOMAS C., Syracuse University, Syracuse, N. Y. December, 1894.
- HOTCHKISS, WILLIAM OTIS, State Geological Survey, Madison, Wis. Dec., 1911.
- *HOVEY, EDMUND OTIS, American Museum of Natural History, New York, N. Y.
- HOWE, ERNEST, Litchfield, Conn. December, 1903.
- HUBBARD, GEORGE D., Oberlin College, Oberlin, Ohio. December, 1914.
- HUDSON, GEORGE H., Plattsburg Normal School, Plattsburg, N. Y. Dec., 1917.
- HUNT, WALTER F., University of Michigan, Ann Arbor, Mich. December, 1914.
- HUNTINGTON, ELLSWORTH, Yale University, New Haven, Conn. Dec., 1906.
- HUSSAKOF, LOUIS, American Museum of Natural History, New York, N. Y. December, 1910.
- HYDE, J. E., Western Reserve University, Cleveland, Ohio. December, 1916.
- JACKSON, A. WENDELL, 9 Desbrosses St., New York, N. Y. December, 1888.
- JACKSON, ROBERT T., Peterborough, N. H. August, 1894.
- JACOBS, ELBRIDGE C., University of Vermont, Burlington, Vt. December, 1921.
- JAGGAR, THOMAS AUGUSTUS, JR., Hawaiian Volcano Observatory, Territory of Hawaii, U. S. A. December, 1906.

- JEFFERSON, MARK S. W., Michigan State Normal College, Ypsilanti, Mich. December, 1904.
- JEFFREY, EDWARD C., Harvard University, Cambridge, Mass. December, 1914.
- JENKINS, OLAF P., State College, Pullman, Wash. December, 1921.
- JOHANNSEN, ALBERT, University of Chicago, Chicago, Ill. December, 1908.
- JOHNSON, B. L., U. S. Geological Survey, Washington, D. C. December, 1919.
- JOHNSON, DOUGLAS WILSON, Columbia University, New York, N. Y. Dec., 1906.
- JOHNSON, ROSWELL H., University of Pittsburgh, Pittsburgh, Pa. Dec., 1918.
- KATZ, FRANK JAMES, U. S. Geological Survey, Washington, D. C. Dec., 1912.
- KAY, GEORGE FREDERICK, State Univ. of Iowa, Iowa City, Iowa. Dec., 1908.
- KEITH, ARTHUR, U. S. Geological Survey, Washington, D. C. May, 1889.
- *KEMP, JAMES F., Columbia University, New York, N. Y.
- KEW, W. S. W., U. S. Geological Survey, Washington, D. C. December, 1920.
- KEYES, CHARLES ROLLIN, 944 Fifth St., Des Moines, Iowa. August, 1890.
- KINDLE, EDWARD M., Victoria Memorial Museum, Ottawa, Canada. Dec., 1905.
- KIRK, CHARLES T., Box 1592, Tulsa, Okla. December, 1915.
- KIRK, EDWIN, U. S. Geological Survey, Washington, D. C. December, 1912.
- KNIGHT, CYRIL WORKMAN, Toronto, Ontario, Canada. December, 1911.
- KNOPE, ADOLPH, Yale Station, New Haven, Conn. December, 1911.
- KNOPE, ELEANORA BLISS, 105 East Rock Road, New Haven, Conn.
- KNOWLTON, FRANK H., U. S. National Museum, Washington, D. C. May, 1889.
- KRAUS, EDWARD HENRY, University of Michigan, Ann Arbor, Mich. June, 1902.
- KÜMMEL, HENRY B., Trenton, N. J. December, 1895.
- *KUNZ, GEORGE F., 401 Fifth Ave., New York, N. Y.
- LAHEE, FREDERIC H., Sun Co., Dallas, Texas. December, 1917.
- LANDES, HENRY, University of Washington, University Station, Seattle, Wash. December, 1908.
- LANE, ALFRED C., Tufts College, Mass. December, 1889.
- LARSEN, ESPER S., JR., U. S. Geological Survey, Washington, D. C. Dec., 1914.
- LAWSON, ANDREW C., University of California, Berkeley, Cal. May, 1889.
- LEE, WILLIS THOMAS, U. S. Geological Survey, Washington, D. C. Dec., 1903.
- LEES, JAMES H., Iowa Geological Survey, Des Moines, Iowa. December, 1914.
- LEIGHTON, MORRIS M., University of Illinois, Urbana, Ill. December, 1921.
- LEITH, CHARLES K., University of Wisconsin, Madison, Wis. Dec., 1902.
- LEONARD, ARTHUR G., State University of North Dakota, Grand Forks, N. Dak. December, 1901.
- LEVERETT, FRANK, Ann Arbor, Mich. August, 1890.
- LEWIS, JOSEPH VOLNEY, Apartado 150, Tampico, Tamps, Mexico. Dec., 1906.
- LIBBEY, WILLIAM, Princeton University, Princeton, N. J. August, 1899.
- LINDGREN, WALDEMAR, Massachusetts Institute of Technology, Cambridge, Mass. August, 1890.
- LISBOA, MIGUEL A. R., Caixa postal 829, Ave. Rio Branco 46-V, Rio de Janeiro, Brazil. December, 1913.
- LITTLE, HOMER P., c/o National Research Council, 1701 Massachusetts Ave., Washington, D. C. December, 1918.
- LLOYD, E. R., c/o Mid Kansas Oil and Gas Co., Mineral Wells, Texas. December, 1919.
- LOGAN, WILLIAM N., Indiana University, Bloomington, Ind. December, 1917.
- LOOMIS, FREDERICK BREWSTER, Amherst College, Amherst, Mass. Dec., 1909.

- LOUDERBACK, GEORGE D., University of California, Berkeley, Cal. June, 1902.
- LOUGHLIN, GERALD F., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- LOW, ALBERT P., 154 McLaren St., Ottawa, Canada. December, 1905.
- LULL, RICHARD SWANN, Yale University, New Haven, Conn. December, 1909.
- LUPTON, CHARLES T., 611 17th St., Denver, Colo. December, 1916.
- MCCALLIE, SAMUEL WASHINGTON, Atlanta, Ga. December, 1909.
- MCCASKEY, HIRAM D., Central Point, Oregon. December, 1904.
- MCCONNELL, RICHARD G., Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.
- MACDONALD, DONALD F., 45 Nassau St., New York City. December, 1915.
- MACFARLANE, JAMES RIEMAN, Woodland Road, Pittsburgh, Pa. August, 1891.
- MCINNES, WILLIAM, Geological and Natural History Survey of Canada, Ottawa, Canada. May, 1889.
- McKELLAR, PETER, Fort William, Ontario, Canada. August, 1890.
- MANSFIELD, GEORGE R., 2067 Park Rd., N. W., Washington, D. C. Dec., 1909.
- MARBUT, CURTIS F., Bureau of Soils, Washington, D. C. August, 1897.
- MARSTERS, VERNON F., 219 Reliance Bldg., Kansas City, Mo. August, 1892.
- MARTIN, GEORGE C., U. S. Geological Survey, Washington, D. C. June, 1902.
- MARTIN, LAWRENCE, Dept. of State, Room 381, Washington, D. C. Dec., 1909.
- MATHER, KIRTLEY F., Denison University, Granville, Ohio. December, 1918.
- MATHEWS, EDWARD B., Johns Hopkins University, Baltimore, Md. Aug., 1895.
- MATSON, GEORGE C., Box 2044, Tulsa, Okla. December, 1918.
- MATTHES, FRANCOIS E., U. S. Geol. Survey, Washington, D. C. Dec., 1914.
- MATTHEW, W. D., American Museum of Natural History, New York. N. Y. December, 1903.
- MAURY, CARLOTTA J., Hastings-on-Hudson, N. Y. December, 1920.
- MAYNARD, THOMAS POOLE, 1622 D. Hurt Bldg., Atlanta, Ga. December, 1914.
- MEAD, WARREN JUDSON, University of Wisconsin, Madison, Wis. Dec., 1916.
- MEINZER, OSCAR E., U. S. Geological Survey, Washington, D. C. Dec., 1916.
- MENDENHALL, WALTER C., U. S. Geol. Survey, Washington, D. C. June, 1902.
- MERRIAM, JOHN C., Carnegie Institution, Washington, D. C. August, 1895.
- MERRILL, GEORGE P., U. S. National Museum, Washington, D. C. Dec., 1888.
- MERWIN, HERBERT E., Geophysical Laboratory, Washington, D. C. Dec., 1914.
- MILLER, ARTHUR M., State University of Kentucky, Lexington, Ky. Dec., 1897.
- MILLER, BENJAMIN L., Lehigh University, South Bethlehem, Pa. Dec., 1904.
- MILLER, WILLET G., Toronto, Canada. December, 1902.
- MILLER, WILLIAM JOHN, Smith College, Northampton, Mass. December, 1909.
- MISER, HUGH D., U. S. Geological Survey, Washington, D. C. December, 1916.
- MOFFIT, FRED HOWARD, U. S. Geological Survey, Washington, D. C. Dec., 1912.
- MOLENGRAAF, G. A. F., Technical High School, Delft, Holland. Dec., 1913.
- MOORE, ELWOOD S., Pennsylvania State College, State College, Pa. Dec., 1911.
- MOORE, RAYMOND C., University of Kansas, Lawrence, Kans. December, 1921.
- MUNN, MALCOLM JOHN, Clinton Bldg., Tulsa, Okla. December, 1909.
- *NASON, FRANK L., West Haven, Conn.
- NELSON, W. A., Tennessee Geological Survey, Nashville, Tenn. Dec., 1920.
- NEWLAND, DAVID HALE, Albany, N. Y. December, 1906.
- NEWSOM, JOHN F., Leland Stanford, Jr., University, Stanford University, Calif. December, 1899.
- NOBLE, LEVI F., Valyermo, Calif. December, 1916.

- NORTON, WILLIAM H., Cornell College, Mount Vernon, Iowa. December, 1895.
NORWOOD, CHARLES J., State University, Lexington, Ky. August, 1894.
O'CONNELL, MARJORIE, American Museum of Natural History, New York, N. Y. December, 1919.
OGILVIE, IDA HELEN, Barnard College, Columbia University, New York, N. Y. December, 1906.
O'HARA, CLEOPHAS C., South Dakota School of Mines, Rapid City, S. Dak. December, 1904.
OHERN, DANIEL WEBSTER, 515 W. 14th St., Oklahoma City, Okla. Dec., 1911.
OLIVEIRA, E. P. DE, Geol. Survey of Brazil, Rio de Janeiro, Brazil. Dec., 1918.
O'NEILL, J. J., Geological Survey of Canada, Ottawa, Canada. Dec., 1920.
OSBORN, HENRY F., American Museum of Natural History, New York, N. Y. August, 1894.
OVERBECK, ROBERT M., U. S. Geological Survey, Washington, D. C. Dec., 1921.
PACK, ROBERT W., American Exchange National Bank Bldg., Dallas, Texas. December, 1916.
PAIGE, SIDNEY, U. S. Geological Survey, Washington, D. C. December, 1911.
PALACHE, CHARLES, Harvard University, Cambridge, Mass. August, 1897.
PARKS, WILLIAM A., University of Toronto, Toronto, Canada. Dec., 1906.
*PATTON, HORACE B., 911 Foster Building, Denver, Colo.
PECK, FREDERICK B., Lafayette College, Easton, Pa. August, 1901.
PENROSE, RICHARD A. F., JR., 460 Bullitt Bldg., Philadelphia, Pa. May, 1889.
PERKINS, GEORGE H., University of Vermont, Burlington, Vt. June, 1902.
PERRY, JOSEPH H., 276 Highland St., Worcester, Mass. December, 1888.
PHALEN, WILLIAM C., The Solvay Process, Syracuse, N. Y. December, 1912.
PHILLIPS, ALEXANDER H., Princeton University, Princeton, N. J. Dec., 1914.
POGUE, JOSEPH E., 29 Fifth Ave., New York City. December, 1911.
POWERS, SIDNEY, Amerada Petr. Corp., Tulsa, Okla. December, 1920.
PRATT, JOSEPH H., North Carolina Geol. Survey, Chapel Hill, N. C. Dec., 1898.
PRATT, W. E., Humble Oil and Refining Co., Houston, Texas. Dec., 1920.
PRICE, WILLIAM A., JR., c/o Humphreys Mexia Co., Mexia, Texas. Dec., 1916.
PRINDLE, LOUIS M., U. S. Geological Survey, Washington, D. C. Dec., 1912.
PROUTY, WILLIAM F., Univ. of North Carolina, Chapel Hill, N. C. Dec., 1911.
*PUMPELLE, RAPHAEL, Newport, R. I.
QUIRKE, TERENCE T., University of Illinois, Urbana, Ill. December, 1921.
RANSOME, FREDERICK L., U. S. Geol. Survey, Washington, D. C. August, 1895.
RAYMOND, PERCY EDWARD, Museum of Comparative Zoölogy, Cambridge, Mass. December, 1907.
REEDS, CHESTER A., American Museum of Natural History, New York, N. Y. December, 1913.
REESIDE, JOHN B., JR., U. S. Geological Survey, Hyattsville, Md. Dec., 1921.
REGER, DAVID B., Box 816, Morgantown, W. Va. December, 1918.
REID, HARRY FIELDING, Johns Hopkins University, Baltimore, Md. Dec., 1892.
REINECKE, LEOPOLD, c/o P. A. Williams, Loanda, Angola, S. W. Africa. December, 1916.
RICE, WILLIAM NORTH, Wesleyan University, Middletown, Conn. August, 1890.
RICH, JOHN LYON, 1101 Adams St., Denver, Colo. December, 1912.
RICHARDS, R. W., U. S. Geological Survey, Washington, D. C. December, 1920.

- RICHARDSON, CHARLES H., Syracuse University, Syracuse, N. Y. Dec., 1899.
- RICHARDSON, GEORGE B., U. S. Geol. Survey, Washington, D. C. Dec., 1908.
- RIES, HEINRICH, Cornell University, Ithaca, N. Y. December, 1893.
- RIGGS, ELMER S., Field Museum of Natural History, Chicago, Ill. Dec., 1911.
- ROBINSON, HENRY HOLLISTER, Hopkins Hall, New Haven, Conn. Dec., 1916.
- RODDY, H. J., State Normal School, Millersville, Pa. December, 1919.
- ROGERS, AUSTIN F., Stanford University, Calif. December, 1918.
- ROSE, BRUCE, 53 Parliament St., London, S. W. I., England. December, 1916.
- ROWE, JESSE PERRY, University of Montana, Missoula, Mont. December, 1911.
- RUEDEMANN, RUDOLF, Albany, N. Y. December, 1905.
- RUTLEDGE, JOHN JOSEPH, McAlester, Okla. December, 1911.
- SALES, RENO H., Anaconda Copper Mining Company, Butte, Mont. Dec., 1916.
- SAYLES, ROBERT WILCOX, Harvard University, Chestnut Hill, Mass. Dec., 1917.
- *SALISBURY, ROLLIN D., University of Chicago, Chicago, Ill.
- SARDESON, FREDERICK W., Univ. of Minnesota, Minneapolis, Minn. Dec., 1892.
- SAVAGE, THOMAS EDMUND, University of Illinois, Urbana, Ill. December, 1907.
- SCHALLER, WALDEMAR T., U. S. Geol. Survey, Washington, D. C. Dec., 1918.
- SCHOFIELD, S. J., University of British Columbia, Vancouver, B. C. Dec., 1918.
- SCHRADER, FRANK C., U. S. Geological Survey, Washington, D. C. Aug., 1901.
- SCHUCHERT, CHARLES, Yale University, New Haven, Conn. August, 1895.
- SCHULTZ, ALFRED R., Hudson, Wis. December, 1912.
- SCOTT, WILLIAM B., Princeton University, Princeton, N. J. August, 1892.
- SEAMAN, ARTHUR E., Michigan College of Mines, Houghton, Mich. Dec., 1904.
- SELLARDS, ELIAS H., University of Texas, Austin, Texas. December, 1905.
- SEMMES, DOUGLAS R., Apartado Postal, 150 Tampico, Tamps, Mexico. December, 1921.
- SHALER, MILLARD K., 66 Rue Des Colonis, Brussels, Belgium. Dec., 1914.
- SHANNON, CHARLES W., Oklahoma Geol. Survey, Norman, Okla. Dec., 1918.
- SHATTUCK, GEORGE BURBANK, Poughkeepsie, N. Y. August, 1899.
- SHAW, EUGENE W., 11 Taylor St., Chevy Chase, Md. December, 1912.
- SHEDD, SOLON, State College of Washington, Pullman, Wash. December, 1904.
- SHEPARD, EDWARD M., 1403 Benton Ave., Springfield, Mo. August, 1901.
- SHIMEK, BOHUMIL, University of Iowa, Iowa City, Iowa. December, 1904.
- SHIMER, HERVEY WOODBURN, Massachusetts Institute of Technology, Cambridge, Mass. December, 1910.
- SHULER, E. W., South Methodist University, Dallas, Texas. December, 1920.
- SIEBENTHAL, CLAUDE E., U. S. Geol. Survey, Washington, D. C. Dec., 1912.
- *SIMONDS, FREDERICK W., University of Texas, Austin, Texas.
- SINCLAIR, WILLIAM JOHN, Princeton University, Princeton, N. J. Dec., 1906.
- SINGEWALD, JOSEPH T., Johns Hopkins University, Baltimore, Md. Dec., 1911.
- SLOAN, EARLE, Charleston, S. C. December, 1908.
- SMITH, BURNETT, Syracuse University, Skaneateles, N. Y. December, 1911.
- SMITH, CARL, Box 1136, Tulsa, Okla. December, 1912.
- *SMITH, EUGENE A., University of Alabama, University, Ala.
- SMITH, GEORGE OTIS, U. S. Geological Survey, Washington, D. C. Aug., 1897.
- SMITH, PHILIP S., U. S. Geological Survey, Washington, D. C. Dec., 1909.
- SMITH, RICHARD A., Biological Survey of Michigan, Lansing, Mich. Dec., 1921.
- SMITH, WARREN DU PRÉ, University of Oregon, Eugene, Ore. December, 1909.
- SMITH, W. S. TANGIER, 640 Tennyson Ave., Palo Alto, Calif. June, 1902.

*SMOCK, JOHN C., Hudson, N. Y.

SMYTH, CHARLES H., JR., Princeton University, Princeton, N. J. Aug., 1892.

SMYTH, HENRY L., Harvard University, Cambridge, Mass. August, 1894.

SOMERS, R. E., Oil and Gas Bldg., University of Pittsburgh, Pittsburgh, Pa. December, 1919.

SOPER, EDGAR K., 120 Broadway, New York City, Room 3101. December, 1918.

SOSMAN, R. B., Geophysical Laboratory, Washington, D. C. December, 1920.

SPEIGHT, ROBERT, Christ Church, Canterbury College, New Zealand. Dec., 1916.

SPENCER, ARTHUR COE, U. S. Geological Survey, Washington, D. C. Dec., 1896.

SPRINGER, FRANK, U. S. National Museum, Washington, D. C. December, 1911.

SPURR, JOSIAH E., c/o Engineering and Mining Journal, 10th Ave. and 36th St., New York, N. Y. December, 1894.

STANLEY-BROWN, JOSEPH, 26 Exchange Place, New York, N. Y. August, 1892.

STANTON, TIMOTHY W., U. S. National Museum, Washington, D. C. Aug., 1891.

STAUFFER, CLINTON R., Univ. of Minnesota, Minneapolis, Minn. Dec., 1911.

STEBINGER, EUGENE, JR., 18 Broadway, New York City. December, 1916.

STEIDTMANN, EDWARD, University of Wisconsin, Madison, Wis. Dec., 1916.

STEPHENSON, LLOYD W., U. S. Geol. Survey, Washington, D. C. Dec., 1911.

*STEVENSON, JOHN J., 215 West 101st St., New York, N. Y.

STOLLER, JAMES HOUGH, Union College, Schenectady, N. Y. December, 1917.

STONE, RALPH WALTER, U. S. Geological Survey, Washington, D. C. Dec., 1912.

STONE, GEORGE WILLIS, U. S. Geological Survey, Washington, D. C. Dec., 1908.

STOUT, WILBER, Geological Survey of Ohio, Columbus, Ohio. December, 1918.

SWARTZ, CHARLES K., Johns Hopkins University, Baltimore, Md. Dec., 1908.

TABER, STEPHEN, University of South Carolina, Columbia, S. C. Dec., 1914.

TAFF, JOSEPH A., 781 Flood Building, San Francisco, Calif. August, 1895.

TALBOT, MIGNON, Mount Holyoke College, South Hadley, Mass. Dec., 1913.

TALMAGE, JAMES E., 47 E. So. Temple St., Salt Lake City, Utah. Dec., 1897.

TARR, WILLIAM ARTHUR, University of Missouri, Columbia, Mo. Dec., 1917.

TAYLOR, FRANK B., Fort Wayne, Ind. December, 1895.

THOMAS, ABRAM O., University of Iowa, Iowa City, Iowa. December, 1921.

TILTON, J. L., Morgantown, W. Va. December, 1920.

*TODD, JAMES E., 905 Missouri Ave., Lawrence, Kans.

TOLMAN, CYRUS FISHER, JR., Leland Stanford, Jr., University, Stanford University, Calif. December, 1909.

TOMLINSON, CHARLES WELDON, 1610 Bixby Ave., Ardmore, Okla. Dec., 1917.

TROWBRIDGE, ARTHUR C., State Univ. of Iowa, Iowa City, Iowa. Dec., 1913.

*TURNER, HENRY W., Mills Building, San Francisco, Calif.

TWENHOFEL, WILLIAM H., University of Wisconsin, Madison, Wis. Dec., 1913.

TWITCHELL, MAYVILLE W., State Geological Survey, Trenton, N. J. Dec., 1911.

TYRRELL, JOSEPH B., Confederation Life Bldg., Toronto, Canada. May, 1889.

UDDEN, JOHAN A., University of Texas, Austin, Texas. August, 1897.

ULRICH, EDWARD O., U. S. Geological Survey, Washington, D. C. Dec., 1903.

UMPLEBY, JOSEPH B., University of Oklahoma, Norman, Okla. Dec., 1913.

*UPHAM, WARREN, Minnesota Historical Society, Saint Paul, Minn.

VAN HORN, F. R., Case School of Applied Science, Cleveland, Ohio. Dec., 1898.

VAN INGEN, GILBERT, Princeton University, Princeton, N. J. December, 1904.

VAN TUYL, FRANCIS M., Colorado School of Mines, Golden, Colo. Dec., 1917.

VAUGHAN, T. WAYLAND, U. S. Geol. Survey, Washington, D. C. August, 1896.

- VEATCH, ARTHUR CLIFFORD, 7 Central Drive, Port Washington, N. Y. December, 1906.
- *VOGDEN, ANTHONY W., 2425 First St., San Diego, Calif.
- WADE, BRUCE, State Geological Survey, Nashville, Tenn. December, 1920.
- *WALCOTT, CHARLES D., Smithsonian Institution, Washington, D. C.
- WALKER, THOMAS L., University of Toronto, Toronto, Canada. Dec., 1903.
- WARING, GERALD A., Port of Spain, Trinidad, B. W. I. December, 1921.
- WARREN, CHARLES H., Massachusetts Institute of Technology, Boston, Mass. December, 1901.
- WASHBURN, C. W., 60 Liberty St., New York, N. Y. December, 1919.
- WASHINGTON, HENRY STEPHENS, Geophysical Laboratory, Washington, D. C. August, 1896.
- WATSON, THOMAS L., University of Virginia, Charlottesville, Va. June, 1900.
- WEAVER, CHARLES E., 264 Herkimer Road, Utica, N. Y. December, 1913.
- WEED, WALTER H., Tuckahoe, N. Y. May, 1889.
- WEGEMANN, CARROLL H., 722 East 7th Ave., Denver, Colo. December, 1912.
- WEIDMAN, SAMUEL, 814 Monett St., Norman, Okla. December, 1903.
- WELLER, STUART, University of Chicago, Chicago, Ill. June, 1900.
- WELLS, ROGER C., U. S. Geological Survey, Washington, D. C. Dec., 1921.
- WESTGATE, LEWIS G., 124 Oak Hill Ave., Delaware, Ohio. August, 1894.
- WHERRY, EDGAR T., Bureau of Chemistry, Washington, D. C. Dec., 1915.
- WHITE, DAVID, U. S. National Museum, Washington, D. C. May, 1889.
- *WHITE, ISRAEL C., Morgantown, W. Va.
- WHITLOCK, H. P., Amer. Museum of Natural History, N. Y. City. Dec., 1920.
- WIELAND, GEORGE REBER, Yale University, New Haven, Conn. December, 1910.
- WILDER, FRANK A., North Holston, Smyth County, Va. December, 1905.
- *WILLIAMS, EDWARD H., JR., Woodstock, Vt.
- WILLIAMS, IRA A., Oregon Bureau of Mines and Geology, 417 Oregon Bldg., Portland, Ore. December, 1905.
- WILLIAMS, MERTON YARWOOD, Geological Survey, Ottawa, Canada. Dec., 1916.
- WILLIS, BAILEY, Leland Stanford, Jr., University, Calif. December, 1889.
- WILSON, ALFRED W. G., Department of Mines, Ottawa, Canada. June, 1902.
- WILSON, MORLEY EVANS, Geological Survey, Ottawa, Canada. December, 1916.
- WINCHELL, ALEXANDER N., University of Wisconsin, Madison, Wis. Aug., 1901.
- WINCHELL, HORACE VAUGHAN, Pacific Mutual Building, Los Angeles, Calif.
- *WINSLOW, ARTHUR, 131 State St., Boston, Mass.
- WOLFF, JOHN E., Harvard University, Cambridge, Mass. December, 1889.
- WOODMAN, JOSEPH E., New York University, New York, N. Y. Dec., 1905.
- WOODRING, WENDELL P., U. S. Geol. Survey, Washington, D. C. Dec., 1921.
- WOODWARD, ROBERT S., Carnegie Institution of Washington, Washington, D. C. May, 1889.
- WOODWORTH, JAY B., Geological Museum, 38 Oxford St., Cambridge, Mass. December, 1895.
- WRIGHT, CHARLES WILL, 28 Vie del Parlamento, Rome, Italy. Dec., 1909.
- WRIGHT, FREDERIC E., Geophysical Laboratory, Carnegie Institution, Washington, D. C. December, 1903.
- ZIEGLER, VICTOR, Colorado School of Mines, Golden, Colo. December, 1916.

CORRESPONDENTS DECEASED

CREDNER, HERMAN. Died July 22, 1913.	SUESS, EDWARD. Died April 20, 1914.
MICHEL-LÉVY, A. Died September, 1911.	TSCHERNYSCHEW, TH. Died Jan. 15, 1914.
ROSENBUSCH, H. Died January 20, 1914.	ZIRKEL, FERDINAND. Died June 11, 1912.

FELLOWS DECEASED

* Indicates Original Fellow (see article III of Constitution)

- *ASHBURNER, CHAS. A. Died Dec. 24, 1889.
- BARLOW, ALFRED E. Died May 28, 1914.
- BARRELL, JOSEPH. Died May 4, 1919.
- BEECHER, CHARLES E. Died Feb. 14, 1904.
- *BECKER, GEORGE F. Died April 20, 1919.
- BELL, ROBERT. Died June 18, 1917.
- BICKMORE, ALBERT S. Died Aug. 12, 1914.
- BLAKE, WM. PHIPPS. Died May 21, 1910.
- BOWMAN, AMOS. Died June 18, 1894.
- BROWN, AMOS P. Died Oct. 9, 1917.
- BUCKLEY, ERNEST R. Died Jan. 19, 1912.
- CAIRNES, D. D. Died June 14, 1917.
- *CALVIN, SAMUEL. Died April 17, 1911.
- CARPENTER, FRANK R. Died April 1, 1910.
- *CHAPIN, J. H. Died March 14, 1892.
- CLARK, WILLIAM B. Died July 27, 1917.
- *CLAYPOLE, EDWARD W. Died Aug. 17, 1901.
- *COMSTOCK, THEO. B. Died July 26, 1915.
- COOK, GEORGE H. Died Sept. 22, 1889.
- *COPE, EDWARD D. Died April 12, 1897.
- CASTILLO, ANTONIO DEL. Died Oct. 28, 1895.
- *CUSHING, H. P. Died April 14, 1921.
- *DANA, JAMES D. Died April 14, 1895.
- DAVIS, CHARLES A. Died April 9, 1916.
- DAWSON, GEORGE M. Died March 2, 1901.
- DAWSON, SIR J. WM. Died Nov. 19, 1899.
- DERBY, ORVILLE A. Died Nov. 27, 1915.
- DRYSDALE, CHAS. W. Died July 10, 1917.
- DUTTON, CLARENCE E. Died Jan. 4, 1912.
- *DWIGHT, WM. B. Died Aug. 29, 1906.
- EASTMAN, CHAS. R. Died Sept. 27, 1918.
- *ELDRIDGE, GEORGE H. Died June 29, 1905.
- *EMMONS, SAMUEL F. Died March 28, 1911.
- FONTAINE, WM. M. Died April 30, 1913.
- *FOOTE, ALBERT E. Died October 10, 1895.
- *FRAZER, PERSIFOR. Died April 7, 1909.
- *FULLER, HOMER T. Died Aug. 14, 1908.
- *GILBERT, GROVE K. Died May 1, 1918.
- GIROUX, N. J. Died November 30, 1891.
- HAGUE, ARNOLD. Died May 14, 1917.
- *HALL, CHRISTOPHER W. Died May 10, 1911.
- *HALL, JAMES. Died August 7, 1898.
- HATCHER, JOHN B. Died July 3, 1904.
- *HAY, ROBERT. Died December 14, 1895.
- HAYES, C. WILLARD. Died Feb. 9, 1916.
- *HEILPRIN, ANGELO. Died July 17, 1907.
- HILGARD, EUGENE W. Died Jan. 8, 1916.
- HILL, FRANK A. Died July 13, 1915.
- *HITCHCOCK, CHAS. H. Died Nov 7, 1919.
- *HOLMES, JOSEPH A. Died July 13, 1915.
- HONEYMAN, DAVID. Died October 17, 1889.
- *HOWELL, EDWIN E. Died April 16, 1911.
- *HOVEY, HORACE C. Died July 27, 1914.
- HUNT, THOMAS S. Died Feb. 12, 1892.
- *HYATT, ALPHEUS. Died Jan. 15, 1902.
- IDDINGS, J. P. Died Sept. 8, 1920.
- IRVING, JOHN D. Died July 26, 1918.
- JACKSON, THOMAS M. Died Feb. 3, 1912.
- *JAMES, JOSEPH F. Died March 29, 1897.
- JULIEN, ALEXIS A. Died May 7, 1919.
- KNIGHT, WILBUR C. Died July 28, 1903.
- LACOE, RALPH D. Died February 5, 1901.
- LAFLAMME, J. C. K. Died July 6, 1910.
- LANBE, L. M. Died March 12, 1919.
- LANGTON, DANIEL W. Died June 21, 1909.
- *LE CONTE, JOSEPH. Died July 6, 1901.
- *LESLEY, J. PETER. Died June 2, 1903.
- LOUGHRIDGE, ROBT. H. Died July 1, 1917.
- MCCALLEY, HENRY. Died Nov. 20, 1904.
- *MCGEE, W. J. Died September 4, 1912.
- MARCY, OLIVER. Died March 19, 1899.
- MARSH, OTHNIEL C. Died March 18, 1899.
- MELL, P. H. Died October 12, 1918.
- *MERRILL, FRED. J. H. Died Nov. 29, 1916.
- MILLS, JAMES E. Died July 25, 1901.
- *NASON, HENRY B. Died January 17, 1895.
- *NEFF, PETER. Died May 11, 1903.
- *NEWBERRY, JOHN S. Died Dec. 7, 1892.
- NILES, WILLIAM H. Died Sept. 12, 1910.
- *ORTON, EDWARD. Died October 16, 1899.
- *OSBORN, AMOS O. Died March, 1911.
- *OWEN, RICHARD. Died March 24, 1890.
- PENFIELD, SAMUEL L. Died Aug. 14, 1906.
- PENHALLOW, DAVID P. Died Oct. 20, 1910.
- PIRSSON, L. V. Died Dec. 8, 1919.
- *PLATT, FRANKLIN. Died July 24, 1900.
- PETTEE, WILLIAM H. Died May 26, 1904.
- *POWELL, JOHN W. Died Sept. 23, 1902.
- *TROSSER, CHAS. S. Died Sept. 11, 1916.
- PURDUE, A. H. Died Dec. 12, 1917.
- ROGERS, G. S. Died Nov. 18, 1919.
- *RUSSELL, ISRAEL C. Died May 1, 1906.
- *SAFFORD, JAMES M. Died July 3, 1907.
- *SCHAEFFER, CHARLES. Died Nov. 23, 1903.
- SEELY, H. M. Died May 4, 1917.
- SEÑA, J. C. DA COSTA. Died June 20, 1919.
- *SHALER, NATHANIEL S. Died Apr. 10, 1906.
- *SPENCER, J. W. Died July, 1921.
- SAINT JOHN, O. H. Died July 17, 1921.
- SUTTON, WILLIAM J. Died May 9, 1915.
- TARR, RALPH S. Died March 21, 1912.
- TIGHT, WILLIAM G. Died Jan. 15, 1910.

- | | |
|---|--|
| *VAN HISE, C. R. Died Nov. 19, 1918. | *WILLIAMS, H. S. Died July 31, 1918. |
| WACHSMUTH, CHAS. Died Feb. 7, 1896. | WILMOTT, ARTHUR B. Died May 8, 1914. |
| WADSWORTH, M. E. Died April 21, 1921. | *WINCHELL, ALEX. Died Feb. 19, 1891. |
| WESTON, THOMAS C. Died July 20, 1910. | *WINCHELL, NEWTON H. Died May 1, 1914. |
| WHITE, THEODORE G. Died July 7, 1901. | WRIGHT, ALBERT A. Died April 2, 1905. |
| *WHITFIELD, ROBT. P. Died April 6, 1910. | *WRIGHT, G. F. Died April 20, 1921. |
| *WILLIAMS, GEORGE H. Died July 12, 1894. | YEATES, WILLIAM S. Died Feb. 19, 1908. |
| *WILLIAMS, J. FRANCIS. Died Nov. 9, 1891. | |

Summary

Correspondents	11
Original Fellows.....	31
Elected Fellows.....	415
Membership.....	457
Deceased Correspondents.....	6
Deceased Fellows.....	117

PROCEEDINGS OF THE TWENTIETH ANNUAL MEETING *
OF THE CORDILLERAN SECTION OF THE GEOLOGICAL
SOCIETY OF AMERICA, HELD AT BERKELEY, CALIFOR-
NIA, MARCH 26, 1921.

AUSTIN F. ROGERS, *Secretary*

CONTENTS

	Page
Session of March 26.....	188
Election of officers for 1921.....	188
Program of papers.....	188
Correlation and paleogeography of the marine tertiary of Cali- fornia [title]; by Bruce L. Clark.....	188
Probable occurrence of massive trolite in serpentine [title]; by A. S. Eakle.....	188
Jurupaite, a new mineral from Crestmore, California [title]; by A. S. Eakle.....	188
Late Tertiary mammalian remains from near Alturas, northeast- ern California [title]; by Chester Stock.....	188
Marsupial from the John Day Oligocene of Logan Butte, Oregon [title]; by Chester Stock and E. L. Furlong.....	189
Mechanics of the San Andreas fault [title]; by Bailey Willis....	189
Certain marked differential movements in the San Francisco Bay region [title]; by G. D. Louderback.....	189
Jasperoid of the Joplin District, Missouri, Kansas, and Oklahoma [title]; by W. S. Tangier Smith.....	189
Collophane, a much-neglected mineral [title]; by Austin F. Rogers	189
Discussion of the age of the Briones formation of middle Cali- fornia [title]; by P. D. Trask.....	189
Montezuma Hills [title]; by G. A. Wilcox.....	189
Some new aspects of the geology at Cobalt [title]; by A. R. Whiteman.....	189
Business session of the Section.....	190
Register of the California meeting, 1921.....	190

* Secretary Rogers, of the Cordilleran Section, telegraphed on June 15, 1922, in response to a telegraphic inquiry of the Editor, that "No meeting of the Cordilleran Section was held at Seattle [in 1920]. The geologists present met with the Pacific Coast Section of the Paleontological Society." In view of this fact, the above meeting of March 26, 1921, becomes the twentieth meeting of the Cordilleran Section instead of the twenty-first, as reported by Secretary Rogers.—EDITOR.

SESSION OF MARCH 26

The twenty-first annual meeting of the Cordilleran Section of the Geological Society of America was held in conjunction with the Pacific Coast Section of the Paleontological Society of America, the Seismological Society of America, and the Le Conte Club, at the University of California, Bacon Hall, on March 26, 1921.

ELECTION OF OFFICERS FOR 1921

President, GEORGE D. LOUDERBACK

Secretary, AUSTIN F. ROGERS

Councilor, CYRUS F. TOLMAN, JR.

The meeting was called to order at 10.30 a. m. by the President.

PROGRAM OF PAPERS

The following papers were presented in the order given:

CORRELATION AND PALEO GEOGRAPHY OF THE MARINE TERTIARY OF CALIFORNIA

BY BRUCE L. CLARK

Presented extemporaneously and illustrated by lantern slides. Discussion by Messrs. Lawson, Willis, Baker, Gester, and Louderback.

PROBABLE OCCURRENCE OF MASSIVE TROILITE IN SERPENTINE

BY A. S. EAKLE

Presented extemporaneously.

JURUPAITE, A NEW MINERAL FROM CRESTMORE, CALIFORNIA

BY A. S. EAKLE

Presented extemporaneously. Discussion by Mr. Lawson.

The Section adjourned for lunch at 12.15.

The afternoon session was called to order by the President at 1.55.

LATE TERTIARY MAMMALIAN REMAINS FROM NEAR ALTURAS, NORTHEASTERN CALIFORNIA

BY CHESTER STOCK

Presented extemporaneously. Discussion by Messrs. Turner and Lawson.

MARSUPIAL FROM THE JOHN DAY OLIGOCENE OF LOGAN BUTTE, OREGON

BY CHESTER STOCK AND E. L. FURLONG

Presented extemporaneously by Mr. Stock.

MECHANICS OF THE SAN ANDREAS FAULT

BY BAILEY WILLIS

Presented extemporaneously. Discussion by Mr. Lawson.

CERTAIN MARKED DIFFERENTIAL MOVEMENTS IN THE SAN FRANCISCO BAY REGION

BY G. D. LOUDERBACK

Presented extemporaneously. Discussion by Messrs. Clark and Turner.

JASPEROID OF THE JOPLIN DISTRICT, MISSOURI, KANSAS, AND OKLAHOMA

BY W. S. TANGIER SMITH

This paper was read in full.

COLLOPHANE, A MUCH-NEGLECTED MINERAL

BY AUSTIN F. ROGERS

Presented extemporaneously and illustrated by lantern slides. Discussion by Messrs. Eakle and Baker.

DISCUSSION OF THE AGE OF THE BRIONES FORMATION OF MIDDLE CALIFORNIA

BY P. D. TRASK

Paper read in full. Discussion by Mr. Louderback.

MONTEZUMA HILLS

BY G. A. WILCOX

Presented extemporaneously.

SOME NEW ASPECTS OF THE GEOLOGY AT COBALT

BY A. R. WHITEMAN

Presented extemporaneously. Discussion by Mr. Weber.

At 6.15 the meeting adjourned for dinner at the Faculty Club. Informal after-dinner talks were made by Dr. J. C. Merriam and Dr. Collier Cobb.

BUSINESS SESSION OF THE SECTION

At the conclusion of the dinner a short business session was held. A motion was made, seconded, and carried that the Executive Committee of the Cordilleran Section be instructed to arrange for the annual meeting of the Section at or near the Easter period of each year.

A motion was made, seconded, and carried that the Executive Committee of the Section be requested to consider the desirability of securing a more permanent tenure of the office of Secretary and to bring in a recommendation in that behalf at the next annual meeting.

It was moved, seconded, and carried that, for the purpose of meetings of the Section held for the reading and discussion of papers, the members of the Society of Economic Geologists be entitled to the privileges of the floor and welcome to participate in excursions or social functions held under the auspices of the Section.

REGISTER OF THE CALIFORNIA MEETING, 1921

F. M. ANDERSON	G. D. LOUDERBACK
B. L. CLARK	J. C. MERRIAM
C. COBB	A. F. ROGERS
A. S. EAKLE	W. S. T. SMITH
A. C. LAWSON	H. W. TURNER
B. WILLIS	

The following visitors were in attendance:

BAKER	A. LOCKE
BAILEY	MILLER
FOLGER	MORSE
E. L. FURLONG	NELSON
G. C. GESTER	J. P. SMITH
H. GESTER	C. STOCK
W. H. GRANT	P. D. TRASK
R. S. HOLWAY	VARNEY
KLINGAMAN	WEBER
LEISER	A. R. WHITMAN
G. A. WILCOX	

PROCEEDINGS OF THE THIRTEENTH ANNUAL MEETING
OF THE PALEONTOLOGICAL SOCIETY, HELD AT AM-
HERST, MASSACHUSETTS, DECEMBER 28-30, 1921.¹

R. S. BASSLER, *Secretary*

CONTENTS

	Page
Session of Wednesday, December 28.....	193
Session of Thursday, December 29.....	193
Report of the Council.....	193
Secretary's report.....	193
Treasurer's report.....	194
Appointment of Auditing Committee... ..	195
Election of officers and members.....	195
New nominations and election to membership.....	196
Presentation of papers.....	196
Nature of <i>Salterella</i> [abstract]; by Thomas H. Clark.....	196
Possible habits of cephalopods and trilobites [abstract]; by Percy E. Raymond.....	197
Historical sketch of paleopathology [abstract]; by Roy L. Moodie	197
<i>Oldhamia</i> in the Lower Cambrian of Massachusetts [abstract]; by B. F. Howell.....	198
Nature of <i>Taonurus</i> and its use in estimating geologic time [abstract]; by J. J. Galloway.....	199
Pennsylvanian faunas of north Texas and their correlation [ab- stract]; by Raymond C. Moore... ..	199
Unattached simple Paleozoic corals [abstract]; by August F. Foerste.....	201
Devonian limestone at Saint George, Quebec [abstract]; by Thomas H. Clark.....	201
Age of the coal beds of the Kaiping coal basin, in northeastern China [abstract]; by A. W. Grabau.....	201
Ordovician formations of north China [abstract]; by A. W. Grabau	202
Presidential address.....	203
Some problems connected with the Dakota sandstone: Presi- dential address by T. W. Stanton.....	203
Supplement to the bibliography and catalogue of the fossil verte- brates of North America; by O. P. Hay	203
Flora of the Payette formation [abstract]; by Ralph W. Chaney.	203

¹ Manuscript received by the Secretary of the Society February 7, 1922.

	Page
Flora of the Rancho La Brea [abstract]; by Ralph W. Chaney...	204
Pines of the Mesozoic and their relationship to older and more modern types [abstract]; by Edward C. Jeffrey.....	204
Ordovician "Hypoparian" genera of trilobites [abstract]; by E. O. Ulrich.....	205
Limits of variations in foraminifera; by J. A. Cushman.....	206
Recent geological work in Gulf Coast oil fields; by E. T. Dumble.	207
Mohawkian and Cincinnati rocks of central Tennessee [abstract]; by R. S. Bassler.....	207
Session of Friday, December 30.....	207
Report of the Auditing Committee.....	207
Presentation of papers.....	207
Few more facts bearing on the correlation of the Chester formations; by E. O. Ulrich.....	208
Occurrence of the Parichnos of Bertrand in certain gymnosperms [abstract]; by E. C. Jeffrey.....	208
Age and development of red beds and the terrestrial vertebrates in the Appalachian and the Kansas-Texas region [abstract]; by J. W. Beede.....	208
Methods of studying Ammonites; by Marjorie O'Connell.....	209
Lunar petrefactions; by F. W. Sardeson.	209
Section of Vertebrate Paleontology.....	209
Presentation of papers.....	209
Fossils of the Connecticut Valley [abstract]; by E. L. Troxell....	209
Hyracodons from the Big Badlands of South Dakota; by W. J. Sinclair.....	209
Relationship of the Great Basin and Great Plains fauna [abstract]; by E. L. Troxell.....	210
Restoration of <i>Blastomeryx</i> ; by R. S. Lull.....	211
Supposed Labyrinthodont footprints from the Maryland Carboniferous [abstract]; by R. S. Lull.....	211
Upper Pawnee Creek beds [abstract]; by F. M. Loomis.....	211
Lower Miocene at Van Tassel, Wyoming; by F. B. Loomis.....	211
Huge amphibian from the Upper Coal Measures of Kansas [abstract]; by H. T. Martin.....	212
Primitive and carnivore-like characters of the Merycoidodontidae [abstract]; by M. R. Thorpe.....	212
Restoration of <i>Eporeodon socialis</i> , Marsh [abstract]; by M. R. Thorpe.....	213
New light on the phylogeny of the Canidae; by W. D. Matthew...	214
Tooth of almost human type from the Lower Pliocene Snake Creek beds of Western Nebraska; by Harold J. Cook.....	214
<i>Aræocyon</i> , a probable Old World migrant [abstract]; by M. R. Thorpe.....	214
Snake Creek fauna; by W. D. Matthew.....	215
Phylogeny and nomenclature of the Proboscidea; by H. F. Osborn	215
Register of the Amherst meeting, 1921.....	216
Officers, Correspondents, and Members of the Paleontological Society.....	217

SESSION OF WEDNESDAY, DECEMBER 28

The general session of the Society, for the presentation of annual reports and other business, scheduled for 2 p. m., Wednesday, December 28, was postponed until Thursday, at 9.30 a. m., in order that the members could attend the section of the Geological Society of America where the stratigraphic and paleontologic papers forming Group B were being read.

Wednesday evening the members participated in a smoker at College Hall with the Geological Society of America and affiliated societies and listened to the address of Prof. J. F. Kemp, its retiring President.

SESSION OF THURSDAY, DECEMBER 29

President Stanton called the thirteenth annual meeting of the Society to order at 9.30 a. m., December 29, in the geological lecture-room of Geology-Biology Building. The first matter of business was the report of the Council.

REPORT OF THE COUNCIL

To the Paleontological Society, in thirteenth annual meeting assembled:

Two meetings of the Council have been held during the year, one following the last annual meeting and the other immediately preceding the present session, all other business having been transacted by correspondence. The Council's administration of the Society's business for the thirteenth year is presented in the following reports:

SECRETARY'S REPORT

To the Council of the Paleontological Society:

The proceedings of the twelfth annual meeting of the Paleontological Society, held at Chicago, Illinois, December 28-30, 1920, are printed in volume 32, number 1, pages 119-156, of the Bulletin of the Geological Society of America, printed March 31, 1921, and distributed to the members.

The announcement that the thirteenth annual meeting of the Society would be held at Amherst, Massachusetts, December 28-30, 1921, as the guest of Amherst College, and the Council's proposed nominations for officers for 1922 was issued February 22, 1921.

Membership.—The Society has lost two of its Correspondents by death during the year—Dr. Henry Woodward, of the British Museum and editor of the Geological Magazine for over 50 years, and Dr. Alfred

Nathorst, of the Royal Natural History Museum, Stockholm, geologist, Arctic explorer, ethnologist, and probably the most eminent student of paleobotany. We have also suffered the loss of one member, Mr. John T. Doneghy. One member has resigned during the year. Four new members have just been elected and three additional nominations are awaiting consideration at the present meeting. This year five of our members have been elected to fellowship in the Geological Society of America. The result of these various changes leaves a total number of members at the end of 1921 as 212.

Publications.—Eight papers published by the Society in the Bulletin of the Geological Society of America, in addition to the Proceedings, have been distributed to the members during the course of the year. With favorable action of the Council, the Secretary has distributed to members elected in recent years a considerable number of duplicate copies of papers printed in the earlier years of the Society.

Respectfully submitted,

R. S. BASSLER,

Secretary.

WASHINGTON, D. C., *December 27, 1921.*

TREASURER'S REPORT

To the Council of the Paleontological Society:

The Treasurer begs to submit the following report of the finances of the Society for the fiscal year ending December 24, 1921:

RECEIPTS

Cash on hand December 22, 1920.....	\$668.68
Membership fees.....	282.55
Interest, Connecticut Savings Bank.....	23.51
	————— \$974.74

EXPENDITURES

Secretary's office:

Secretary's allowance.....	\$50.00
Office expenses.....	57.74
Clerical help.....	25.00
	————— \$132.74

Treasurer's office:

Treasurer's allowance.....	\$25.00
Printing and postage.....	13.25
	————— 38.25

Geological Society of America:

Printing programs, etcetera.....	\$10.50
Reprints.....	115.98
	————— 126.48

Pacific Coast Section:

Assessment for the American Association for the Advancement of Science.....	5.00
	302.47

Balance on hand December 24, 1921.....	\$672.27
--	----------

Net increase in funds.....	\$3.59
----------------------------	--------

Outstanding dues (1921), 7.....	21.00
---------------------------------	-------

Respectfully submitted,

(Signed)

RICHARD S. LULL,

*Treasurer.*NEW HAVEN, CONNECTICUT, *December 24, 1921.*

APPOINTMENT OF AUDITING COMMITTEE

President Stanton appointed Messrs. Raymond and Cushman as a committee to audit the Treasurer's accounts, following the reading of the Council's report.

ELECTION OF OFFICERS AND MEMBERS

The result of the Ballots for the election of officers for 1922 and of new members was then announced, as follows:

*OFFICERS FOR 1922**President:*

W. D. MATTHEW, New York City

First Vice-President:

E. S. RIGGS, Chicago, Ill.

Second Vice-President:

E. W. BERRY, Baltimore, Md.

Third Vice-President:

B. L. CLARK, Berkeley, Calif.

Secretary:

R. S. BASSLER, Washington, D. C.

Treasurer:

RICHARD S. LULL, New Haven, Conn.

Editor:

WALTER GRANGER, New York City

NEW MEMBERS

WALTER SCOTT ADKINS, Bureau of Economic Geology, Austin, Texas.

ANTONIO PASTOR GIRAUD, care Transcontinental de Petroleo, S. A., Tampico, Mexico.

A. S. ROMER, Department of Geology, Columbia University, New York City.

ARTHUR J. TIEJE, Department of Geology, University of Colorado, Boulder, Colorado.

NEW NOMINATIONS AND ELECTION TO MEMBERSHIP

Three nominations to membership which had arrived too late for the printed ballot and which had received the approval of the Council were then presented to the Society:

Miss ALVA C. ELLISOR, A. B. University of Texas, paleontologist of the Humble Oil and Refining Company, 803 Humble Building, Houston, Texas. Proposed by B. L. Clark and Chester Stock.

FRED WILLIS DARBY, engaged in care and preparation of the Marsh collection of fossil vertebrates since 1908, Peabody Museum, Yale University, New Haven, Connecticut. Proposed by R. S. Lull, Charles Schuchert, and C. O. Dunbar.

FRANK HARRIS McLEARN, Ph. D. Yale (1917), associate invertebrate paleontologist, Geological Survey of Canada, Ottawa, Canada. Proposed by Charles Schuchert, E. M. Kindle, and R. S. Lull.

It was then voted that the By-Laws be suspended and that the vote of the Society for the election to membership of these three nominees be cast by the Secretary.

There being no further business, the Society proceeded to the reading of scientific papers in general session, with President Stanton in the chair.

PRESENTATION OF PAPERS

The first paper on the program, dealing with the molluscan genus *Salterella* and showing its possible cephalopod affinities, was presented by the author and illustrated by drawings. Discussion by Messrs. Foerste, Ulrich, and Chadwick.

NATURE OF *SALTERELLA*

BY THOMAS H. CLARK

(Abstract)

Since 1863 the genus *Salterella* has been included in the class Pteropoda, although its position there has always been in some doubt. A large collection of specimens from Lévis, Quebec, has enabled the writer to make a more or less thorough study of these little fossils. Although in some specimens ex-

ternal shells are present, the individuals consist for the most part of septa placed one within the other, the larger of which possess a "septal neck." This, in connection with other characteristics, has led the writer to the conclusion that in *Salterella* we have the most primitive cephalopod known. The relation of *Salterella* to *Volborthella* is considered and a revision of the species of *Salterella* is submitted.

An interesting account of recent cephalopods and of the possible habits of these animals, and also of the trilobites, was given in the next paper, presented by the author and illustrated with many well selected lantern slides. Discussion by Messrs. Foerste and Clarke.

POSSIBLE HABITS OF CEPHALOPODS AND TRILOBITES

BY PERCY E. RAYMOND

(Abstract)

Knowledge of the anatomy of trilobites has become sufficiently full to allow a reasonable speculation as to the mode of life and habits of these animals. Many writers have made suggestions, and the more plausible have been brought together and illustrated by drawings which are the work of Mr. Charles Fish, of Providence, Rhode Island.

Less has been written upon the cephalopods, but a comparison of the shells of Recent and Paleozoic forms and a study of the anatomy and habits of the modern nautilus suggest certain possible reconstructions. The importance of the shell in the economy of the animal is emphasized.

In the absence of the author, the next paper was read by the Secretary and discussed by Dr. Clarke.

HISTORICAL SKETCH OF PALEOPATHOLOGY

BY ROY L. MOODIE

(Abstract)

Pathological conditions on the fossil bones of extinct animals were first recognized and described among the Pleistocene mammals, especially the cave mammals of Europe.

The earliest reference to pathological conditions of this nature was made by E. J. C. Esper, a professor in the university of Erlangen, in 1774. He referred to an injured femur of a cave bear, interpreting the lesion as an osteosarcoma. Eighty years later Mayer concluded that the injury was an infected fracture with considerable callus. Goldfuss, von Soemmering, and Cuvier in 1820-23 drew many interesting conclusions concerning the habits of the extinct mammals, based on their observations of the injuries. William Clift in 1823 read a paper to the Royal Society of London describing certain injured and diseased bones of bovine animals. These specimens are said to be still preserved in the Hunterian Museum.

The first memoir devoted entirely to paleopathology was not by a paleontologist but by a surgeon, von Walther of Bonn. The Natural History Museum

of Bonn had acquired a number of bones of Pleistocene mammals, some of which exhibited interesting lesions. Von Walther published his memoir in 1825, and was much impressed by the undoubted evidences of disease, thousands of years old, which he very carefully described. His interpretations of these remains were confirmed seventy years later by the eminent pathologist, Rudolph Virchow.

Ten years later (1835) the subject was further advanced by P. C. Schmerling, a Belgian paleontologist, who wrote and illustrated the finest memoir thus far produced relating to paleopathology. His material was chiefly Pleistocene mammals. A physician, Mayer, in 1854 produced the next important contribution, in which he reviewed all the preexisting literature. His results were accompanied by fine lithographic plates. The studies of Virchow in 1870 and later in 1895 were likewise devoted to remains of Pleistocene mammals.

So far, the literature of paleopathology was of European origin entirely. Except for incidental references to pathological conditions by Leidy, Osborn, Hatcher, Volz, Schlosser, Wieland, Lull, Gilmore, and others, no definite attempt was made to advance the science of paleopathology of extinct animals until 1912, when Abel reviewed the whole field in his work on *Paleobiologie*. Abel deserves the credit of perceiving a new field of work on the pathology of vertebrate fossils—a field which had already been cultivated in America among the invertebrates by Clarke.

In 1913 the entire subject received the impetus of Ruffers' genius. He saw the whole field as one, and combined for the first time observations on ancient man, as seen in the Egyptian mummies, and extinct animals. The field of study involved in the subject of paleopathology thus includes the Paleozoic invertebrates, among which disease may have had its inception, the fossil vertebrates, and ancient man. To these interesting fields of observation Sudhoff of Germany and Escomel of Peru have recently added observations on ancient surgical instruments, which have been recently shown to be the cause of certain types of ancient pathology. The subject thus merges with the history of medicine.

The Secretary then presented the following paper for the author and called attention to the algal nature of a specimen of the much-discussed fossil *Oldhamia* which was exhibited.

OLDHAMIA IN THE LOWER CAMBRIAN OF MASSACHUSETTS

BY B. F. HOWELL

(Abstract)

Specimens, apparently referable to the much-discussed and variable Irish fossil, *Oldhamia* (*Murchisonites*) *antiqua* (Forbes), have recently been collected from the purple shales of one of the well known Lower Cambrian exposures of Pearl Street, Weymouth, Massachusetts, by Mr. Stinson Lord, of Quincy, who has presented them to the Paleontological Museum of Princeton University. They are well preserved and seem almost certainly to be referable to some form of alga, and not to be mere inorganic markings. This

species was first described from Ireland more than half a century ago, but the exact age of the beds containing it there has never been definitely determined. The fact that the shales in which it occurs at Weymouth are of Lower Cambrian age argues for a similar age for the Irish beds.

Another problematical organism formed the subject of the next paper, presented by the author and illustrated by specimens. Discussion by Messrs. Chadwick, Ulrich, Moore, and Clarke.

NATURE OF TAONURUS AND ITS USE IN ESTIMATING GEOLOGIC TIME

BY J. J. GALLOWAY

(Abstract)

Taonurus is regarded as the burrow of a sedentary worm which lived in brackish water on a growing delta. *Taonurus caudagalli* is a structure which appears in vertical sections of the Esopus grit as horizontal series of crescent-in-crescent forms, in layers about one-fourth inch in thickness, extending horizontally many feet and made by different individuals. Most of the rock is composed of this structure. *Taonurus caudagalli* appears to have been formed by worms burrowing horizontally in a layer of mud, each burrow being about an eighth of an inch from the last. The burrow next to the one being formed collapsed and formed the crescents. After a fresh layer of mud one-fourth inch thick was laid down the new annual crop of worms worked over that layer, sometimes working over the top of the former layers. If the layers of silt represent annual layers, the 700 feet of Esopus grit, exclusive of the marine Schoharie, was deposited in about 34,000 years.

The characteristics and correlation of the faunas of the Pennsylvanian rocks of north Texas were then described by the author; discussion by E. O. Ulrich.

PENNSYLVANIAN FAUNAS OF NORTH TEXAS AND THEIR CORRELATION

BY RAYMOND C. MOORE

(Abstract)

Recent studies based on large collections of invertebrate fossils from the Pennsylvanian formations of north-central Texas indicate that three main faunal groups may be recognized: (1) that from the Bend, (2) that from the Strawn, Canyon, and lower Cisco, and (3) that from the middle and upper Cisco. While these are broadly related, there are distinguishing features which readily differentiate them. As similar faunal groups may be observed in the Pennsylvanian rocks of neighboring areas, there is furnished a fairly satisfactory basis for paleontologic correlation. However, the Pennsylvanian rocks of the Midcontinent region do not appear to be divisible on the basis of faunal distinctions into very minute, widely traceable units.

The Bend fauna, found in the strata of the Marble Falls limestone and Smithwick shale, is marked chiefly by an element which is suggestive of the

Mississippian, by the absence of many of the commonest fossils of the later Pennsylvanian, and by the presence of a considerable number of species which are restricted to this fauna. It closely resembles the fauna of the Wapanucka limestone of southern Oklahoma and that of the Morrow group in northeastern Oklahoma and northern Arkansas. It is the oldest known marine Pennsylvanian fauna in North America.

The second main faunal group is found in the rocks of the Strawn, Canyon, and lower Cisco. It contains a large assemblage of mollusks, among which are many of the most characteristic and widely distributed species of the period. Because of its very typical development and remarkably perfect preservation in the Wewoka formation of southern Oklahoma, where it has been described excellently by Dr. George H. Girty, this associated group of invertebrates may conveniently be designated as the Wewoka fauna. The composition of the fauna found in the Mineral Wells (upper Strawn) formation in north Texas is almost the same as that of the type Wewoka fauna. The Canyon formations, which are dominantly calcareous, contain a modification of the Wewoka fauna which is apparently a normal consequent of the clearer waters of this time. In the lower Cisco a recurrence of the typical Wewoka assemblage, with its numerous molluscan species, is seen in the remarkably fossiliferous shales of the upper part of the Graham formation. While this fauna contains a number of species which are restricted to Texas, a very large proportion is identical with the southern Oklahoma species. The stratigraphic divisions in Oklahoma which are faunally equivalent to the formations designated in Texas include most or all of the strata from the Atoka to Holdenville, in the Colgate region, and beds below the Ochelata, in northeastern Oklahoma. In Kansas, Missouri, and States to the north, the faunal group regarded as equivalent to that described in Texas does not range above the Kansas City formation.

The fossils from the remaining portion of the Texas Pennsylvanian comprise a faunal group which is distinctive of the closing epoch in the period. It lacks an important element of the Wewoka fauna and is characterized by the appearance of several new species which are abundant and widely distributed in the rocks of the upper Pennsylvanian, some of them living on into the Lower Permian. The middle and upper Cisco which contains this fauna may be correlated closely with the Lansing to Wabaunsee formations of Kansas and their equivalents in adjoining States.

The lines of division between these main faunal groups appear to coincide with important interruptions in the deposition of sediments in the Pennsylvanian seas of the Midcontinent region and reflect broadly the physical history of the period. There is a considerable stratigraphic break between the Bend and succeeding deposits. The uplift of the Arbuckle Mountains and the spreading of much clastic debris across northern Texas and Oklahoma is associated with the change in the invertebrate faunas which is observed in the later Pennsylvanian.

The author of the following paper presented interesting observations upon the matter of attachment of the Paleozoic cup corals. Discussion by Messrs. Ulrich, Chadwick, and Bassler.

UNATTACHED SIMPLE PALEOZOIC CORALS

BY AUGUST F. FOERSTE

(Abstract)

Most simple *Tetracoralla* show no attachment areas. In many species only occasional specimens show attachment areas. Most attachment areas are too small to have supported the corallum except during its immature stages of growth. Mature coralla of most species were free. A few species with flattened sides apparently were adapted for drifting along the bottom of the sea with changing currents. Some of these were provided with opercula. Other forms may have lived with their apical ends more or less buried in mud or sand. Some of the radiciform offshoots from the epitheca may have served to anchor the specimens in loose mud or sand. Species represented only by attached specimens have relatively large attachment areas.

The paleontology and paleogeographic significance of an isolated outcrop of Devonian limestone 60 miles south of Quebec formed the subject of the next paper, presented by the author.

DEVONIAN LIMESTONE AT SAINT GEORGE, QUEBEC

BY THOMAS H. CLARK

(Abstract)

On the Chaudière River, about 60 miles southeast of Quebec, there is a small outcrop of Onondaga limestone with an abundant coral fauna. This limestone has been mentioned in geological literature but twice: first, by Logan, in 1863, and again, by Ells, in 1888. In company with Dr. P. E. Raymond, the writer visited this outcrop last summer and collected fossils from it. These are described and their significance with respect to the paleogeography of Onondaga time is discussed.

Stratigraphic results in the Paleozoic rocks of China obtained by Dr. A. W. Grabau, paleontologist of the Chinese Geological Survey, were given in the final two papers of the morning session, read by the Secretary in the absence of the author.

AGE OF THE COAL BEDS OF THE KAIPING COAL BASIN, IN NORTHEASTERN CHINA

BY A. W. GRABAU

(Abstract)

In the Kaiping coal basin of eastern Chihli Province, north China, thirteen coal seams (bituminous) are recognized. The lowest of these (number 13) is 35 centimeters in thickness, and its roof is formed by an impure limestone with crinoidal fragments, 30 centimeters thick, above which lies a massive argillutite, often pyritiferous and containing a marine fauna of Lower

Permian affinities. Seventeen species have so far been differentiated, the best preserved and specifically determinable ones being of types elsewhere found in the Lower Permian of China. In shales above this horizon, but not accurately located (probably from seam 12 or higher), a fairly perfect specimen and several fragments of *Eurypterus* (*E. chinensis*) have been found. The flora from the several seams worked is a mixture of Stephanian and younger types, many Permian elements being present. The conclusion from the evidence so far obtained is that the coals are not older than Lower Permian. About 35 meters below seam number 13 is a very fossiliferous limestone (Tangshan limestone), generally less than a meter in thickness and containing numerous specimens of *Spirifer bisulcatus* Sowerby, *Lithostrocion kaipingense*, and other fossils, identical with or allied to Viséan species of western Europe. This is, therefore, believed to represent a Dinantian (Mississippian) horizon. It is possible, but doubtful, that part of the intervening 35 meters may represent Moscovian or Uralian horizons, but so far no satisfactory paleontological evidence has been obtained.

The Tangshan limestone lies about 85 meters above the top of the Machiakou, or *Actinoceras*, limestone of Black River age. The intervening beds are red shales, fireclays, shales, and sandstones of Mississippian age. There is no Silurian or Devonian in north China.

ORDOVICIAN FORMATIONS OF NORTH CHINA

BY A. W. GRABAU

(Abstract)

The Ordovician is represented in north China by at least 800 meters of somewhat dolomitic limestones, with, locally, some intercalated shales. In the Kaiping coal basin of eastern Chihli Province the Ordovician rests disconformably on an erosion surface of highest Cambrian, beginning with a basal conglomerate, the pebbles of which are formed from the underlying Cambrian calcilutites. These lowest Ordovician beds (Yehli limestone) have so far yielded only two species of *Suecoceras*. Eight hundred meters higher the limestones (*Actinoceras* or Machiakou limestones) contain a fairly rich fauna which shows the closest affinity with the Black River fauna of North America. Cephalopods and gastropods predominate. There are seven species of *Actinoceras* and eight species of *Lophospira*, besides others. The most remarkable feature of this fauna is its almost complete distinctness from the fauna of equivalent age found in south China, the two having scarcely a species in common. The Ordovician fauna from south China has European affinities, while that of north China is of the North American type.

Fifty miles north of the Kaiping basin, near the Manchurian border, a well marked Lower Ordovician fauna has been discovered by Dr. F. F. Mathieu, of the Kailan Mining Administration. This ranges through about 500 meters of rocks (mostly calcareous) and shows a remarkable affinity to the Beekmantown fauna of the Champlain region. It contains *Ophileta*, *Piloceras*, *Cameroceras*, *Protocameroceras*, and the new holochroanitic cephalopod, *Chihlioceras*, representing a new family, the *Chihlioceratidae*. It also contains *Archæocyathus* of the same type as that found on the Mingan Islands, and, like that,

referable to the genus *Archæoscyphia* Hinde. The base of the series is not exposed, and it is disconformably succeeded by Coal Measures strata, the Machiakou or Actinoceras limestone being absent here. Three horizons are recognizable in this lower series, but their relation to the Yehli limestone is not yet clear. So far, there have been recognized in the Ordovician rocks of north China 31 genera and 58 species, 45 of these being specifically identified. All except five of these are new. Three new genera and one new family have been obtained.

The meeting then adjourned for luncheon.

PRESIDENTIAL ADDRESS

At 2.30 the Society met to hear the address of the retiring President of the Paleontological Society, entitled

SOME PROBLEMS CONNECTED WITH THE DAKOTA SANDSTONE

PRESIDENTIAL ADDRESS BY T. W. STANTON

The reading of papers before the Society in general session was then resumed, the first of the afternoon session being an account of the supplementary work upon the bibliographic catalogue of North American fossil vertebrates, including its plan, stage of completion, and prospect of its publication.

SUPPLEMENT TO THE BIBLIOGRAPHY AND CATALOGUE OF THE FOSSIL VERTEBRATES OF NORTH AMERICA

BY O. P. HAY

In the discussion which followed this paper it was voted unanimously by the members that representation be made to the Director of the U. S. Geological Survey to the effect that it was the hope of the Paleontological Society that Dr. Hay's catalogue be published as speedily as practicable.

Following this discussion the members interested in vertebrate paleontology retired to an adjoining room to meet in special session for the consideration of their more technical papers.

In the general session papers upon paleobotanical subjects were then read. The first two, bearing upon Cenozoic floras, were combined by the author, who gave an idea of the paleobotanic work carried on by him under the auspices of the Carnegie Institution.

FLORA OF THE PAYETTE FORMATION

BY RALPH W. CHANEY

(Abstract)

The flora of the Payette formation was originally considered to be of Miocene age, but in recent years it has been referred to the Upper Eocene because

of the presence in it of several Upper Glarno species. Collections during the past season have increased the number of species known from the flora and have shown a dominance of Miocene species which occur in the Mascall of Oregon. The occurrence of several Eocene species suggests that the Payette is somewhat older than the Mascall. It differs from the latter in having abundant sycamores, poplars, and other lowland types, indicating a habitat somewhat different from that in which the Mascall sediments were laid down.

FLORA OF THE RANCHO LA BREA

BY RALPH W. CHANEY

(Abstract)

The abundance of vertebrate remains from the Rancho La Brea deposits of southern California has emphasized the paucity of the fossil plants. The only well defined leaves which have been secured are those of an oak much like the living *Quercus agrifolia*; a few acorns resembling those of the same species have also been obtained. Cones of the knob-cone pine, *Pinus attenuata*, and of the Monterey cypress, *Cupressus macrocarpa*, are present in small numbers, and there is an abundance of wood which has been referred to *Cupressus*.

During the past summer a considerable amount of tar was carefully examined, but, aside from wood, a few undetermined seeds and stems resembling those of aquatic plants were the only materials collected. Further search may uncover situations where plants accumulated in abundance, but, on the basis of the material at hand, it appears that conditions did not favor the accumulation of plants. A possible explanation for these unfavorable conditions may be that the level topography did not permit much transportation of leaves and fruits, and that an arid or semiarid climate restricted the number of arborescent types much as it does today. The habitat indications of the known flora are quite consistent with this explanation.

The next paper, presented by the author and illustrated by many instructive lantern slides, was of special interest on account of its wide scope and general subject-matter.

PINES OF THE MESOZOIC AND THEIR RELATIONSHIP TO OLDER AND MORE MODERN TYPES

BY EDWARD C. JEFFREY

(Abstract)

The author has had the opportunity of studying recently many hundreds of specimens of Cretaceous representatives of pines and allied forms. It is clear from such studies that there were interesting types present at the epoch transitional between our modern pines and still more ancient types. It is a well established fact that existing pines are characterized by a definite and small number of needles in each cluster or short shoot. In the Cretaceous there were types with many needles on a short shoot. Further in the midst of the needles was a cluster of rudimentary leaves indicating a less degree of

specialization than in the modern species, where only the visible leaves of the fascicle are present and in limited number. In addition to these transitional forms, which represent both the hard and soft pines of the present epoch, there were other forms more nearly resembling our existing pines in having a definite limited number of fascicular leaves, namely, from two to five, but clearly contrasted to living pines in the fact that they possessed rudimentary leaves in the midst of the fascicular leaves. A third variant was represented by the genus *Prepinus*, in which the leaves are not only numerous in a fascicle with a leafy central growing region, but also characterized in contrast to the foliar organs of all other living gymnosperms by the presence of centripetal or cryptogamic wood. In this respect, as in many other, they present a striking resemblance to the leaves of the *Cordaitales*. The bearing of these facts on the conventional view that the Araucarian conifers are the oldest is discussed.

New facts on the structure of the hypoparian trilobites were described in the next paper, which was illustrated with lantern slides; remarks by Dr. Raymond.

ORDOVICIAN "HYPOPARIAN" GENERA OF TRILOBITES

BY E. O. ULRICH

(Abstract)

The author discussed the character, interrelations, stratigraphic position, and geologic distribution of the Agnostidæ, Trinucleidæ, Harpedidæ, and Ampyxidæ found in Ordovician formations in America. Most of these trilobites were shown to have originated in the North Atlantic realm, from which they invaded the Appalachian Valley troughs. Only *Cryptolithus* seems to have had a more southern origin, most of its species having invaded the interior continental seas by way of the Mississippi embayment.

In general, the author definitely disapproved the prevailing view that the marginal suture in the Trinucleidæ and Harpedidæ corresponds to the facial suture. He inclined instead to the opposing view, that the facial suture in these trilobites ran as in the Opisthoparia and became closed by fusion early in the life of individuals. He held that the marginal suture became a necessary convenience in moulting and possible through lateral and then posterior extension of the epistoma. In other words, the marginal suture represents a continuance of the frontal suture of most Opisthoparia to the genal angles. He pointed out also that *Olenellus* has a ventral plate that is comparable to the ventral plate of the cephalon of *Harpes*. As is well known, the facial suture in *Olenellus* is quite as thoroughly fused as in *Harpes*. The author exhibited enlarged photographs of the latter indicating that this suture followed essentially the same Opisthoparian course in both of these genera. It was concluded, therefore, that the Order Hypoparia must either be abandoned or preferably redefined. The author also questioned the desirability of the family Endymionidæ, recently proposed by Raymond, and dissents from the prevailing practice of referring all Ordovician Harpedidæ except *Harpides* to *Eoharpes*. He prefers to return most of them to the genus *Harpes*.

The Ampyxidæ were discussed at length and the genera of the family re-

defined. *Raphiophorus* Angelin could not be separated satisfactorily from *Ampyx*, but *Lonchodomus* of the same authority proved easily and constantly distinguishable by differences in the facial suture and in the anterior margin of the cephalon.

A new genus, *Ampyxina*, is proposed for small Ampyridæ with small and very short rostral spine, obovate glabella, a small pair of isolated posterior lateral glabellar lobes, and four or five thoracic segments. The pygidium also differs from that of *Ampyx* and *Lonchodomus* in wanting the thick, beveled and striated posterior edge. In *Ampyx* the second and third pairs of lateral glabellar lobes often are rather well developed and partly separated from the middle lobe, but the posterior pair is seldom well defined and never isolated. Six species of the new genus are known, only one of which has been described and figured, and this without either a generic or specific name. The description and figures referred to were published in 1909, by R. R. Rowley, in "The Geology of Pike County," Missouri Bureau of Geology and Mines, second series, volume 8, page 60, plate 15, figures 12-14. The species is not uncommon in the basal part of the Maquoketa shale west of Louisiana, Missouri, and along the Mississippi bank two or three miles above Thebes, Illinois. I propose now to call it *Ampyxina bassleri* n. sp., and to designate it provisionally as the genotype of *Ampyxina*. The other species are all older—Lower Trenton and Upper Chazy. One occurs with *Cryptolithus* n. sp. in the Viola limestone in Oklahoma, another in the basal 10 feet of the Martinsburg shale at Chambersburg, Pennsylvania, and three others in subcrystalline limestone lying just beneath the Athens shale, near Blacksburg and Saltville, Virginia, and near Albany and other places in Tennessee. One of the last three may be the same as *Raphiophorus powelli* Raymond.

The genera mainly concerned in these studies are *Agnostus*, *Ampyx*, *Lonchodomus*, *Ampyxina*, *Trinucleus*, *Cryptolithus*, *Harpes*, and *Eoharpes*?. The species and varieties of each have been most critically determined, and as thus conceived have proved themselves of great value as guide fossils in correlating the Chazy and Mohawkian formations in the Appalachian region. Publication of the species will proceed as opportunities offer.

Under the following title the author brought out the fact that the foraminifera hitherto supposed to be extremely variable are in reality not so at all, for a close study of both fossil and recent species has shown much of this so-called variation to be due either to unrecognized stages in development, the peculiar alternation of generations developed in this group, or to the lack of close discrimination of specific characters.

LIMITS OF VARIATIONS IN FORAMINIFERA

BY J. A. CUSHMAN

An interesting paper describing the paleontological work being done in the Gulf Coast oil fields by the oil companies located at Houston, Texas, was then presented by Miss Esther E. Richards for the author.

RECENT GEOLOGICAL WORK IN GULF COAST OIL FIELDS

BY E. T. DUMBLE

The concluding paper of the afternoon dealt with the stratigraphy of central Tennessee, especially with reference to the significance of the distribution of the various formations. Illustrated by lantern slides; discussed by Messrs. Raymond, Ulrich, and Reeds.

MOHAWKIAN AND CININNATIAN ROCKS OF CENTRAL TENNESSEE

BY R. S. BASSLER

(Abstract)

The Carters, Lowville, and Kimmswick formations, of Black River age; the Curdsville, Hermitage, Bigby, Cannon, and Catheys formations, of Mohawkian age, and the Leipers formation, of Cincinnatian age, all rather easily distinguished faunally and lithologically, prove in the course of extensive mapping to be developed quite unequally on different sides of the Nashville dome. For example, the Carters limestone is thickest on the western side, while the overlying Lowville limestone is thickest on the eastern side; the Kimmswick limestone outcrops only on the southern flank, while the next younger formation, the Curdsville limestone, is found only on the northern side. The chief reason for these differences is believed to be due to oscillation, and the great development of phosphatic rock in the Hermitage, Bigby, Catheys, and Leipers formation is considered as likewise connected with the same phenomenon.

At 5.30 p. m. the Society adjourned until the next day.

Thursday evening at 7 o'clock the annual dinner of the Geological Society of America and affiliated societies was held at College Hall of Amherst College, in which our members participated.

SESSION OF FRIDAY, DECEMBER 30

President Stanton called the general section of the Society to order Friday morning at 9.30, while the vertebrate paleontologists continued in special session.

REPORT OF THE AUDITING COMMITTEE

The chairman of the Auditing Committee read a statement attesting to the correctness of the Treasurer's accounts, and it was then voted that the report be accepted.

PRESENTATION OF PAPERS

The first paper on the program comprised new evidence on the Chester problem, presented by the author, who discussed critical sections in the area under discussion to prove his points.

FEW MORE FACTS BEARING ON THE CORRELATION OF THE CHESTER FORMATIONS

BY E. O. ULRICH

A paleobotanical subject followed, illustrated by lantern slides, which showed the clearness and detail that can be obtained in thin sections of fossil plants.

OCCURRENCE OF THE PARICHNOS OF BERTRAND IN CERTAIN GYMNASPERMS

BY E. C. JEFFREY

(Abstract)

The structure of Parichnos is well known for *Lepidodendron* and *Sigillaria*. The author has found similar structures in certain living gymnosperms. They accompany the leaf-traces from the surface of the central cylinder out to the base of the leaf, where they end in the spongy central green substance of the leaf. Sometimes the Parichnos of gymnosperms appear as canals and sometimes merely as strands of richly aëriferous parenchyma. Their significance from the physiological and morphological standpoints is discussed, as well as the possibility of their indicating relationship between the gymnosperms in which they are found and the Lepidophyta.

The final paper presented at the meeting was an interesting discussion given by the author.

AGE AND DEVELOPMENT OF RED BEDS AND THE TERRESTRIAL VERTEBRATES IN THE APPALACHIAN AND THE KANSAS-TEXAS REGION

BY J. W. BEEDE

(Abstract)

1. Review of postulate regarding uneven development of Red Beds and Permian terrestrial vertebrates of the Appalachian and Western Plains provinces of the United States.

2. Review of development of marine invertebrates and plants in these regions during Pennsylvanian and Permian times, which show relatively little progress during upper Pennsylvanian time and a marked quickening of the evolutionary processes at the beginning of Permian time.

3. Review of the history of the vertebrate life during this time, and the conclusion that it, too, has, so far as known, relatively little expansion during the upper Pennsylvanian, with marked expansion, specialization, and change of fundamental aspect beginning at the base of the Permian and continuing at least until the close of the Clear Fork epoch of the Permian.

4. Demonstration of the accumulation of Red Beds deposits earlier in the Pennsylvanian period in the Wichita Mountain region than any now preserved in the rocks of the Pennsylvanian period of Ohio, West Virginia, and Pennsylvania.

In the absence of the authors, the following papers were read by title:

METHODS OF STUDYING AMMONITES

BY MARJORIE O'CONNELL

LUNAR PETREFACTIONS

BY F. W. SARDESON

At noon the Society adjourned.

SECTION OF VERTEBRATE PALEONTOLOGY

Members interested in vertebrate paleontology formed a separate section Thursday, at 3.30 p. m., with Dr. W. J. Sinclair presiding.

PRESENTATION OF PAPERS

In the first paper of the session Dr. Troxell summarized briefly the few discoveries of dinosaurs, aside from footprints, that had been made in the Newark sandstones of the Connecticut Valley, with additional data of the circumstances of each discovery secured by him in field-work last summer, and showed certain problematic fossils which he had found.

FOSSILS OF THE CONNECTICUT VALLEY

BY EDWARD L. TROXELL

(Abstract)

About a dozen specimens of reptiles have been found in the Newark series of New England, showing that they are remarkably rare as compared to the number and variety of the footprints; none of those known are large enough to have made certain of the footprints, which measure 20 inches in length.

A search during the summer resulted in the finding of one or more undoubted bone fragments of the smaller *Anchisaurus*, and other fragments which are doubtfully referred to the larger reptiles. Other interesting material was found: silicified and carbonized wood, *Unio* shells of a new variety, footprints in a new locality, and fish from the well known black shales.

HYRACODONS FROM THE BIG BADLANDS OF SOUTH DAKOTA

BY W. J. SINCLAIR

(Abstract)

Comparison of a large series of dentitions from the various levels of the White River enabled the author to determine certain characters, especially in the premolars, as constant and valid specific distinctions. Size was found to

be extremely variable and the species do not appear to be good horizon-markers.

A discussion followed concerning the standards of species distinction and methods of description among fossil mammals, in which the author, Dr. Troxell, Dr. Thorpe, Professor Lull, Dr. W. D. Matthew, and Dr. O. P. Hay participated.

In the next paper the author proposed to transfer the Harrison and Rosebud group of formations of the Great Plains to the Oligocene, correlating them with the John Day formation of Oregon, and included in the Miocene the Clarendon, Loup Fork, and Santa Fé marls, referred to the Pliocene by previous writers. The paper was discussed by Dr. Matthew, who dissented from the changes proposed.

RELATIONSHIP OF THE GREAT BASIN AND GREAT PLAINS FAUNA

BY EDWARD L. TROXELL

(Abstract)

The study of the vertebrate fossils in the Marsh Collection from these two widely separated regions suggests a new arrangement of the stratigraphic column, which is here presented, with the conclusion that the Arikaree is not Lower Miocene, but Upper Oligocene, and that the dividing line between the latter and the true Miocene should be above the Rosebud and Harrison formations.

Great Plains		Great Basin
Lower Miocene	} Pawnee Creek.	Mascall.
		Columbia lavas.
Unconformity.		Upper Oligocene
Upper Oligocene	Rosebud-Harrison.	Upper John Day.
(Arikaree)	Monroe Creek-Gering	Middle John Day.

Not only is there a great similarity between the John Day formation of Oregon and the Arikaree of Dakota and Nebraska, but these strata seem to be synchronous with the Oligocene of the Old World.

The following important groups of animals reach extinction in the Arikaree: The hypothetical Upper Oligocene entelodont (*Dinohyus*), *Steneofiber*, *Dicera-therium* (*Canopus*, *Metacænopus*, *Menoceras*), *Eporeodon-Mesoreodon*, *Leptauchenia*, *Mesohippus-Miohippus*, *Protoceras-Syndyoceras*, and *Hypisodus*, while with the true Miocene we have the introduction of the proboscideans, teleocerine rhinoceroses, and horned artiodactyls.

The meeting was then adjourned.

The session of the Vertebrate Section was resumed at 9.30 a. m., Friday, December 30, Dr. Sinclair in the chair. The following papers were presented:

RESTORATION OF *BLASTOMERYX*

BY R. S. LULL

The author showed photographs of a mounted skeleton of *Blastomeryx* in the Peabody Museum, with the form of the body restored on one side. It is based on two individuals from the later Miocene. The species shows well developed lanian tusks and a rudimentary horn over the orbit, unlike the Lower Miocene species described by Matthew.

Dr. Matthew remarked that the *Blastomeryx* described by Scott in 1891, also probably from the Upper Miocene, had a rudimentary horn.

SUPPOSED LABYRINTHODONT FOOTPRINTS FROM THE MARYLAND
CARBONIFEROUS

BY R. S. LULL

(Abstract)

The series of footprints described were exposed on a considerable surface of shale. They were not as clear in detail as might be desired, but represented a large animal, comparable in size to *Pareiosaurus*.

A large limb-bone from the Pennsylvanian of West Virginia, submitted some years ago to the Society by Dr. I. C. White, was thought to represent a type that might be responsible for such footprints as the author described. Dr. White's specimen was considered as pretty certainly a natural cast of a limb-bone, although some authorities had questioned it.

Discussed by Dr. Matthew and Dr. Wieland.

UPPER PAWNEE CREEK BEDS

BY F. B. LOOMIS

(Abstract)

During field-work last summer the author had verified the existence of a distinct upper fossil zone overlying the true Pawnee Creek beds in Weld County, Colorado, as suspected by Matthew and Osborn from faunal studies. The fauna was of Lower Pliocene age, but with a considerable admixture of redeposited fossils from the true Pawnee Creek beds.

LOWER MIOCENE AT VAN TASSEL, WYOMING

BY F. B. LOOMIS

(Abstract)

A rich fossiliferous pocket in the Lower Harrison beds close to the village of Van Tassel had been profitably exploited by the author and was well worth further work. The fauna contains elements which are found at Agate, Nebraska, but differs in being dominantly a deposit of Oreodonts. The collection from this region is described, there being several new species, and a horse, *Parahippus tyleri*, which gives a much more complete idea of this formerly little known type. The fauna fills in much that is lacking at Agate and gives with the Agate forms a much more balanced idea of the life of the time.

In the next paper, read by Dr. Matthew, the author describes footprints of which plaster casts were exhibited.

HUGE AMPHIBIAN FROM THE UPPER COAL MEASURES OF KANSAS

BY H. T. MARTIN

(Abstract)

A huge amphibian is indicated in a series of footprints recently discovered in the sandstone of the Upper Coal Measures of Kansas. The impressions, measuring some 7 inches in length and 6 inches in breadth, extend for a distance of 25 feet with slight interruptions, along a sandstone ledge, which is regarded as a phase of the Weston shales, lying immediately below the Kickapoo (Iatan) limestone, exposed on the banks of the Wakarusa Creek, near Dightmans Crossing, some 5 miles southeast of Lawrence, Kansas.

Some of the impressions are very well preserved, and indicate four toes on the front feet and five on the hind feet, for which reason I think an amphibian is indicated. Large amphibians are known from the Kansas Coal Measures by the footprints described by Mudge and Marsh from Osage County and by skeletal remains described by Moodie from Washington County. A much larger type of vertebrate is indicated by the present footprints, however; in fact, we may say that these footprints represent the largest land vertebrates so far recorded from the pre-Triassic rocks. The majority of Coal Measures amphibians are extremely small, measuring only a few inches in length; but the animal which made these tracks must have been from 15 to 20 feet in length and is comparable in size to *Mastodonsaurus* of the European Triassic.

In the following paper the primitive characters of the Merycoidodontidæ were listed in some detail, showing a considerable approach to the Creodonta and primitive Carnivora as compared with the higher artiodactyls. Dr. Matthew remarked on the desirability of instituting more exact comparisons with the Eocene Artiodactyla as known principally from the European formations.

*PRIMITIVE AND CARNIVORE-LIKE CHARACTERS OF THE
MERYCOIDODONTIDÆ*

BY MALCOLM RUTHERFORD THORPE

(Abstract)

The type of this great group was described by Dr. Joseph Leidy in April, 1848. Subsequently he pointed out resemblances between *Merycoidodon* and the peccary, the camel, and the wolf, and characterized this family as "ruminating hogs," a name which has since clung to the whole group.

There are some twenty-six genera and subgenera in the Merycoidodont family, with about fourteen in the pre-Miocene, and it is the latter which are herein considered. The Eocene and Oligocene species show a close similarity in structure. The late Oligocene and early Miocene was a very important

time in the racial history of the Oreodont family, and from this period they began to diverge into various terminal lines of development, leading finally to complete extinction.

In summary of the various supposedly primitive and carnivoroid characters, we find twenty-six major primitive and twenty-four carnivoroid, of which approximately one-half are common to both. These may be listed as follows:

(1) Characters which are both primitive and carnivoroid: (*a*) Dolichocephaly, (*b*) well marked postorbital constriction, (*c*) prominent sagittal crest, (*d*) high overhanging occiput, (*e*) relatively large head, (*f*) more or less elongate face, (*g*) very large temporal fossa, (*h*) palate narrow and somewhat arched transversely, (*i*) presence of well developed canines, (*j*) long body and long tail, (*k*) short legs, and (*l*) dorso-lumbar vertebral formula of 19-20.

(2) Characters which are primitive: (*a*) Stout, heavy zygomata, (*b*) long, robust, downwardly-projecting paroccipitals, (*c*) relatively large lacrymal bone, (*d*) well developed milk dentition, (*e*) complete dentition of forty-four teeth, (*f*) probable omnivorous habit, (*g*) brachyodonty, (*h*) large spine on axis, (*i*) large size of lumbar compared with dorsals, (*j*) broad blade of scapula, (*k*) five digits in manus, (*l*) stout puboischiadic symphysis of pelvis, (*m*) relatively small pelvic outlet, and (*n*) absence of bullæ in the earlier forms.

(3) Characters which are carnivoroid: (*a*) Broad mandibular coronoid, (*b*) long mandibular symphysis, (*c*) incisors subtransverse, (*d*) relative positions of basicranial foramina, (*e*) relatively large infra-orbital foramen, (*f*) tongue and groove articulation on lumbar zygapophyses, (*g*) spine of scapula dividing it into two subequal parts, (*h*) position of acromium and metacromium, (*i*) humerus and ulna, (*j*) metapodials long, slender, keeled (phalanges and ungues), (*k*) femur and tibia, (*l*) semi-digitigrade.

The author's use of the term primitive is only relative—that is, the characters which he considers generalized in this group are, in some instances, not so in other groups. Some of these also may be secondary developments, due to muscle responses or other causes, such as may have produced the heavy zygomata and robust paroccipitals and the possible omnivorous habit.

The carnivoroid characters may be secondary, as Doctor Matthew considers to be the case in *Agriochærus*, or they may be primary, which does not seem to be an unreasonable supposition.

The author of the next paper showed lantern slides of a mounted skeleton and restoration in the Museum of Yale University. Although listed generally as from Oregon, this species is really from the Upper Oligocene of Nebraska.

RESTORATION OF *EPOREODON SOCIALIS*, MARSH

BY MALCOLM RUTHERFORD THORPE

(Abstract)

One of the two cotype skeletons of this genus and species has just been mounted at the Peabody Museum of Yale University. After the skeleton was

erected the restoration of the flesh was made by Professor Lull, based on a most careful study of the musculature of recent animals. The muscles were built up over the actual bones and every attention was paid to the rugose bone surfaces for muscle attachment, which clearly gave evidence of the size and power of each muscle. The result is a rather doglike animal and gives one an entirely different conception of the appearance and character of these animals than that conveyed by Leidy's phrase, "ruminating hogs."

Slides of this mount were shown, as well as those of six other mounts of different genera and species in different museums. It appears to the writer that in the majority of the mounts the attitude seems a little too piglike, and that the probable semi-digitigrade gait is not sufficiently emphasized. Some of these mounts appear to have the head somewhat more elevated than in the specimen at Yale.

The Yale specimen is now in process of casting, in order to insure greater permanency of the flesh restoration. The final result will be the equivalent of a panel mount, but with the plaster reconstruction in place of the usual panel.

NEW LIGHT ON THE PHYLOGENY OF THE CANIDÆ

BY W. D. MATTHEW

A series of skulls of Canidæ from the Lower Snake Creek Upper Miocene of Nebraska was obtained last summer by the American Museum Expedition. These show the intermediate stages between the Canidæ of the Oligocene and the Pleistocene and recent members of the family. Huxley's arrangement of the family into alopecoid and thooid divisions is wholly rejected, the modern Canidæ being divided into two groups, one including *Cyon*, *Icticyon*, and *Lycaon*, the other all the remaining genera. These two groups are derived through two parallel series of ancestral stages from the Eocene *Cynodictis*. The extinct group of Amphicyonine dogs is derivable from the Lower Oligocene *Daphænus* through several intermediate stages, and the Middle Eocene genus, *Miacis*, is probably the common ancestor of the family. The various stages are represented by a series of skulls from the different Tertiary horizons.

TOOTH OF ALMOST HUMAN TYPE FROM THE LOWER PLIOCENE SNAKE CREEK BEDS OF WESTERN NEBRASKA

BY HAROLD J. COOK

Read by Dr. W. J. Sinclair.

The only example of the Simocyonid group of Canidæ in North America formed the subject of the next paper.

AREOCYON, A PROBABLE OLD WORLD MIGRANT

BY MALCOLM RUTHERFORD THORPE

(Abstract)

In the American Journal of Science for June, 1921, I described the lower jaw of a carnivore collected in the Rattlesnake formation of Oregon in 1874

through the efforts of Prof. O. C. Marsh. For this carnivore I proposed the name *Pliocyon marshi*. Subsequently, in the same Journal, for January, 1922, I substituted the name *Aræocyon*.

The presence of this lower jaw in Middle Pliocene deposits of the New World is exceedingly interesting, as it is the only specimen of its kind described or reported from the ancient fauna of North America.

Structurally, *Aræocyon* is remarkably close to *Simocyon primigenius* Roth and Wagner from the Pikermi deposits (Upper Miocene) of Greece. The faunal affinities of the Pikermi genera are with those of Africa rather than with Europe, but we also find a similar faunal phase eastward in Samos and at Maragha, Persia, while in general the fauna of the latter approaches very closely to that of the Pliocene of the Siwaliks in southern Asia and of China.

In the Pliocene, Asia and North America were connected by land and intercontinental faunal migrations took place. Owing to the general eastward trend of the fauna, as mentioned above, it is not unreasonable to suppose that the carnivores also followed the other groups, and that there might have been a concentration of carnivore types in the constricted region of this "game trail" at what is now known as Bering Strait. During the gradually increasing cooling of the northern region in the Pliocene, it became necessary for the fauna in the main to migrate southward—a movement which, if this theory be true, was carried on by *Aræocyon* as far south as Oregon. Therefore my view at present, and Professor Lull is in agreement with it, is that some of the members of the genus *Simocyon* migrated from southern Europe through Asia and into North America during the latter part of the Upper Miocene and the first half of the Pliocene, and that the time involved was sufficiently long for the former representatives of *Simocyon* to develop into *Aræocyon*.

On the other hand, if *Aræocyon* is an autochthonous form, then we must place it in the pseudo-canoid phylum, namely, those with the trenchant-heeled inferior molars, wherein we find *Daphænus*, *Temnocyon*, *Enhydrocyon*, *Cyon*, *Icticyon*, and *Lycæon*.

If this lower jaw on which *Aræocyon* is established had been collected in the Pliocene of Europe, I should have no hesitation in referring it to the genus *Simocyon* or possibly to a subgenus under it, and if *Aræocyon* should finally prove to be autochthonous, then it will be one of the most remarkable cases of convergence on record.

A summary of the results of the American Museum Expedition last summer in the Snake Creek fossil quarries, Miocene and Pliocene of western Nebraska, was given under the following title:

SNAKE CREEK FAUNA

BY W. D. MATTHEW

There was then presented by title

PHYLOGENY AND NOMENCLATURE OF THE PROBOSCIDEA

BY HENRY FAIRFIELD OSBORN

The session was then adjourned.

REGISTER OF THE AMHERST MEETING, 1921

ROBERT ANDERSON	JESSE HYDE
R. S. BASSLER	E. C. JEFFREY
J. W. BEEDE	S. H. KNIGHT
E. B. BRANSON	RICHARD S. LULL
THOMAS C. BROWN	K. F. MATHER
GEORGE H. CHADWICK	W. D. MATTHEW
RALPH W. CHANEY	GEORGE F. MATTHEW
THOMAS H. CLARK	MARJORIE O'CONNELL
JOHN M. CLARKE	PERCY E. RAYMOND
HERDMAN F. CLELAND	CHESTER A. REEDS
HORACE N. CORYELL	JOHN B. REESIDE
JOSEPH A. CUSHMAN	ESTHER E. RICHARDS
CARL O. DUNBAR	A. S. ROMER
ALVA G. ELLISOR	CHARLES SCHUCHERT
RICHARD M. FIELD	WILLIAM J. SINCLAIR
AUGUST F. FOERSTE	T. W. STANTON
J. J. GALLOWAY	MIGNON TALBOT
CLARENCE E. GORDON	MALCOLM R. THORPE
WINIFRED GOLDRING	EDWARD L. TROXELL
CHRIS A. HARTNAGEL	EDWARD O. ULRICH
O. P. HAY	T. WAYLAND VAUGHAN
G. R. WIELAND	

OFFICERS, CORRESPONDENTS, AND MEMBERS OF THE
PALEONTOLOGICAL SOCIETY

OFFICERS FOR 1922

President:

W. D. MATTHEW, New York City

First Vice-President:

E. S. RIGGS, Chicago, Ill.

Second Vice-President:

E. W. BERRY, Baltimore, Md.

Third Vice-President:

B. L. CLARK, Berkeley, Calif.

Secretary:

R. S. BASSLER, Washington, D. C.

Treasurer:

RICHARD S. LULL, New Haven, Conn.

Editor:

WALTER GRANGER, New York City

MEMBERSHIP, 1922

CORRESPONDENTS

BUCKMAN, S. S., Esq., Westfield, Thame, England.

DÉPERET, Prof. CHARLES, University of Lyon, Lyon (Rhône), France.

CANU, FERDINAND, 18 Rue du Peintre Lebrun, Versailles, France.

MEMBERS

ADAMS, L. A., State Teachers' College, Greeley, Colo.

AGUILERA, JOSÉ G., Instituto Geológico de Mexico, City of Mexico, Mexico.

ALDRICH, TRUMAN H., 1036 Glen Iris Avenue, Birmingham, Ala.

AMI, HENRY M., Geological Survey of Canada, Ottawa, Canada.

ANDERSON, F. M., 2604 Etna Street, Berkeley, Calif.

ANDERSON, ROBERT, 47 Parliament St., Westminster, S. W. I., London, England.

ARMSTRONG, EDWIN J., 954 West Ninth Street, Erie, Pa.

ARNOLD, RALPH, 639 South Spring Street, Los Angeles, Calif.

BAGG, RUFUS M., JR., Lawrence College, Appleton, Wis.

BAKER, CHARLES L., Rock Island County, Cordova, Ill.

BARBOUR, ERWIN H., University of Nebraska, Lincoln, Nebr.

- BARROWS, ALBERT L., 1702 Massachusetts Avenue, Washington, D. C.
BARTSCH, PAUL, U. S. National Museum, Washington, D. C.
BASSLER, HARVEY, U. S. Geological Survey, Washington, D. C.
BASSLER, RAY S., U. S. National Museum, Washington, D. C.
BEEDE, JOSHUA W., 1711 San Antonio Street, Austin, Texas.
BELL, WALTER A., Geological Survey of Canada, Ottawa, Canada.
BENSLEY, B. A., University of Toronto, Toronto, Ontario.
BERRY, EDWARD W., Johns Hopkins University, Baltimore, Md.
BIBBINS, ARTHUR B., 2600 Maryland Avenue, Baltimore, Md.
BOSTWICK, THOMAS A., 43 Livingston Street, New Haven, Conn.
BRANSON, E. B., University of Missouri, Columbia, Mo.
BROWN, BARNUM, American Museum of Natural History, New York City.
BROWN, THOMAS C., Laurel Bank Farm, Fitchburg, Mass.
BRYANT, WILLIAM L., Buffalo Society of Natural Sciences, Buffalo, N. Y.
BURLING, LANCASTER D., Whitehall Petroleum Corporation, 53 Parliament Street, Westminster, London, S. W., England.
BUTTS, CHARLES, U. S. Geological Survey, Washington, D. C.
BUWALDA, JOHN P., Bacon Hall, University of California, Berkeley, Calif.
CAMP, CHARLES L., American Museum of Natural History, New York City.
CASE, ERMINE C., University of Michigan, Ann Arbor, Mich.
CHADWICK, GEORGE H., University of Rochester, Rochester, N. Y.
CHANEY, RALPH W., Old Science Hall, Iowa City, Iowa.
CLARK, BRUCE L., University of California, Berkeley, Calif.
CLARK, THOMAS H., 36 Irving Street, Cambridge, Mass.
CLARKE, JOHN M., Education Building, Albany, N. Y.
CLELAND, HERDMAN F., Williams College, Williamstown, Mass.
CLEMENTS, F. E., Desert Laboratory, Tucson, Ariz.
COOK, HAROLD J., Agate, Nebr.
COOKE, C. WYTHE, U. S. Geological Survey, Washington, D. C.
CORYELL, HORACE N., Dept. of Geology, Columbia University, New York City.
CRANE, WILL E., 208 13th Street N. E., Washington, D. C.
CROZEL, GEORGES, 17 Chemin des Celestins, Oullins (Rhône), France.
CUMINGS, EDGAR R., Indiana University, Bloomington, Ind.
CUSHMAN, JOSEPH A., Sharon, Mass.
DALL, W. H., U. S. National Museum, Washington, D. C.
DEAN, BASHFORD, Columbia University, New York City.
DECKER, CHARLES E., University of Oklahoma, Norman, Okla.
DICE, LEE RAYMOND, Department of Zoology, University of Illinois, Urbana, Ill.
DICKERSON, ROY E., 320 Masonic Temple, Manila, P. I.
DOUGLASS, EARL, Carnegie Museum, Pittsburgh, Pa.
DUBOIS, HENRY M., Box 539, La Grande, Oreg.
DUNBAR, CARL O., Department of Geology, Yale University, New Haven, Conn.
EATON, GEORGE F., 70 Sachem Street, New Haven, Conn.
EYERMAN, JOHN, "Oakhurst," Easton, Pa.
FIELD, RICHARD M., Brown University, Providence, R. I.
FOERSTE, AUGUST F., 129 Wroe Avenue, Dayton, Ohio.
FRICK, CHILDS, 70th Street and Central Park, New York City.
GALLOWAY, J. J., Department of Geology, Columbia University, New York City.
GARDNER, JULIA A., U. S. Geological Survey, Washington, D. C.

- GESTER, G. S., Standard Oil Building, San Francisco, Calif.
GIBB, HUGH, Peabody Museum, Yale University, New Haven, Conn.
GILBERT, J. Z., Los Angeles High School, Los Angeles, Calif.
GLICK, PERRY A., 502 East Springfield Street, Champaign, Ill.
GORDON, CLARENCE E., Massachusetts Agricultural College, Amherst, Mass.
GOULD, CHARLES N., 408 Terminal Building, Oklahoma City, Okla.
GRABAU, AMADEUS W., Government University of Peking, Peking, China.
GRANGER, WALTER, American Museum of Natural History, New York City.
GREENE, F. C., 11 Nebraska Building, Tulsa, Okla.
GREGORY, W. K., American Museum of Natural History, New York City.
GRIER, NORMAN McD., Biological Laboratory, Washington and Jefferson College, Washington, Pa.
GOLDRING, WINIFRED, Education Building, Albany, N. Y.
GURLEY, WILLIAM F. E., 6151 University Avenue, Chicago, Ill.
HANNIBAL, HAROLD, Dept. of Geology, Stanford University, Stanford, Calif.
HARRIS, GILBERT D., Cornell University, Ithaca, N. Y.
HARTNAGEL, CHRIS A., Education Building, Albany, N. Y.
HAY, O. P., U. S. National Museum, Washington, D. C.
HAYNES, WINTHROP P., 74 Beacon Street, Hyde Park, Mass.
HEATH, EUGENE SCHOFIELD, 78 West North Avenue, Atlanta, Ga.
HENDERSON, JUNIUS, University of Colorado, Boulder, Colo.
HIBBARD, RAYMOND R., 908 Michigan Avenue, Buffalo, N. Y.
HOLLAND, WILLIAM J., Carnegie Museum, Pittsburgh, Pa.
HOLLICK, ARTHUR, New York Botanical Garden, New York City.
HOWE, HENRY V., 1514 Alder Street, Eugene, Oreg.
HOWELL, B. F., Department of Geology, Princeton University, Princeton, N. J.
HUBBARD, BELA, Woods Hole, Mass.
HUDSON, GEORGE H., 19 Broad Street, Plattsburg, N. Y.
HUME, GEORGE S., Geological Survey of Canada, Ottawa, Canada.
HUSSAKOF, LOUIS, American Museum of Natural History, New York City.
HYDE, JESSE, Western Reserve University, Cleveland, Ohio.
JACKSON, ROBERT T., Peterborough, N. H.
JEFFREY, E. C., Harvard University, Cambridge, Mass.
JENNINGS, OTTO E., Carnegie Museum, Pittsburgh, Pa.
KELLOGG, REMINGTON, Bureau of Biology, U. S. Department of Agriculture, Washington, D. C.
KEMPER, DOROTHY B., 2527 Benvenue Street, Berkeley, Calif.
KEW, W. S. W., U. S. Geological Survey, Washington, D. C.
KINDLE, EDWARD M., Geological Survey of Canada, Ottawa, Ontario.
KIRK, EDWIN, U. S. Geological Survey, Washington, D. C.
KNIGHT, S. H., University of Wyoming, Laramie, Wyo.
KNOWLTON, FRANK H., U. S. Geological Survey, Washington, D. C.
LEE, WILLIS T., U. S. Geological Survey, Washington, D. C.
LEONARD, H. M., Morton Street, Porterville, Calif.
LOEL, WAYNE FREDERICK, General Petroleum Corporation, Higgins Building, Los Angeles, Calif.
LOOMIS, FREDERICK B., Amherst College, Amherst, Mass.
LULL, RICHARD S., Yale University, New Haven, Conn.
LUTHER, D. D., Naples, N. Y.

- McBRIDE, THOMAS H., University of Iowa, Iowa City, Iowa.
McGREGOR, J. H., Columbia University, New York City.
MANSFIELD, WENDELL C., U. S. Geological Survey, Washington, D. C.
MARK, CLARA G., Dept. of Geology, Ohio State University, Columbus, Ohio.
MARTIN, BRUCE, Waukena, Tulare County, Calif.
MATHER, K. F., Denison University, Granville, Ohio.
MATTHEW, W. D., American Museum of Natural History, New York City.
MATTHEW, GEORGE F., 115 Carmarthen Street, St. John, N. B.
MAYNARD, T. POOLE, 1622 D. Hunt Building, Atlanta, Ga.
McEWAN, EULA D., Simpson College, Indianola, Iowa.
MEHL, MAURICE G., University of Missouri, Columbia, Mo.
MERRIAM, JOHN C., Carnegie Institution, Washington, D. C.
MESLER, RECTOR D., U. S. Geological Survey, Washington, D. C.
MILLER, PAUL C., Walker Museum, University of Chicago, Chicago, Ill.
MOODIE, ROY L., University of Illinois, Congress and Honore Sts., Chicago, Ill.
MOODY, CLARENCE L., University of California, Berkeley, Calif.
MOOK, CHARLES C., American Museum of Natural History, New York City.
MOORE, R. C., University of Kansas, Lawrence, Kans.
MORAN, ROBERT B., 408 South Spring Street, Los Angeles, Calif.
MORSE, WILLIAM C., Department of Geology, Mississippi Agricultural and Mechanical College, Agricultural College, Miss.
MOSES, FLORENCE EMMA, 1819 Addison Street, Berkeley, Calif.
NARRAWAY, JAMES E., Department of Justice, Ottawa, Canada.
NELSON, NORMAN E., 116 East 8th Street, Fort Worth, Texas.
NELSON, RICHARD N., 2237 Durant Avenue, Berkeley, Calif.
NOÉ, ADOLF CARL, University of Chicago, Chicago, Ill.
NOMLAND, JORGEN O., 200 Bush Street, San Francisco, Calif.
O'CONNELL, MARJORIE, American Museum of Natural History, New York City.
OSBORN, HENRY FAIRFIELD, American Museum of Natural History, N. Y. City.
PACK, R. W., U. S. Geological Survey, Washington, D. C.
PACKARD, EARL L., Eugene, Oreg.
PALMER, KATHERINE VAN WINKLE, University of Washington, Seattle, Wash.
PARKS, WILLIAM A., University of Toronto, Toronto, Ontario.
PATTEN, WILLIAM, Dartmouth College, Hanover, N. H.
PETERSON, O. A., Carnegie Museum, Pittsburgh, Pa.
PETRUNKEVITCH, ALEXANDER, 266 Livingston Street, New Haven, Conn.
PRICE, WILLIAM A., JR., 1320 Great Southern Life Building, Dallas, Texas.
RAYMOND, PERCY E., Museum of Comparative Zoology, Cambridge, Mass.
REEDS, CHESTER A., American Museum of Natural History, New York City.
REESIDE, JOHN B., JR., U. S. Geological Survey, Washington, D. C.
RESSER, CHARLES E., U. S. National Museum, Washington, D. C.
RICHARDS, ESTHER E., Rio Bravo Oil Company, Southern Pacific Building, Houston, Texas.
RIGGS, E. S., Field Museum of Natural History, Chicago, Ill.
ROBINSON, WILBUR I., Geological Survey of Michigan, Lansing, Mich.
ROUNDY, PAUL V., U. S. Geological Survey, Washington, D. C.
ROWLEY, ROBERT R., Louisiana, Mo.
RUEDEMANN, RUDOLF, Education Building, Albany, N. Y.
RUSSELL, RICHARD JOEL, 2412 Piedmont Avenue, Berkeley, Calif.

- SARDESON, FREDERICK W., 414 Harvard Street, Minneapolis, Minn.
SARLE, CLIFTON J., University of Arizona, Tucson, Ariz.
SAVAGE, THOMAS E., University of Illinois, Urbana, Ill.
SCHUCHERT, CHARLES, Yale University, New Haven, Conn.
SCOTT, WILLIAM B., Princeton University, Princeton, N. J.
SELLARDS, ELIAS H., University of Texas, Austin, Texas.
SHIDELER, WILLIAM H., Miami University, Oxford, Ohio.
SHIMER, HERVEY W., Massachusetts Institute of Technology, Boston, Mass.
SINCLAIR, WILLIAM J., Princeton University, Princeton, N. J.
SLOCOM, ARTHUR WARE, Walker Museum, University of Chicago, Chicago, Ill.
SMITH, BURNETT, Syracuse University, Syracuse, N. Y.
SPRINGER, FRANK, U. S. National Museum, Washington, D. C.
STANTON, T. W., U. S. Geological Survey, Washington, D. C.
STAUFFER, CLINTON R., University of Minnesota, Minneapolis, Minn.
STEPHENSON, L. W., U. S. Geological Survey, Washington, D. C.
STERNBERG, CHARLES H., Lawrence, Kans.
STOCK, CHESTER, 2839 Forest Avenue, Berkeley, Calif.
STONER, REGINALD C., Standard Oil Building, San Francisco, Calif.
STRICKLAND, FRANK PETER, JR., 640 Oakland Street, Kansas City, Mo.
SWARTZ, CHARLES K., Johns Hopkins University, Baltimore, Md.
TALBOT, MIGNON, Mt. Holyoke College, South Hadley, Mass.
TELLER, EDGAR E., 66 Highland Street, Buffalo, N. Y.
THOMAS, A. O., University of Iowa, Iowa City, Iowa.
THOMPSON, ALBERT, American Museum of Natural History, New York City.
THORPE, MALCOLM R., Osborn Zoological Laboratory, Yale University, New Haven, Conn.
TRASK, PARKER DAVIES, 1502 Alice Street, Oakland, Calif.
TROXELL, EDWARD L., Osborn Zoological Laboratory, Yale University, New Haven, Conn.
TWHENHOFEL, WILLIAM H., University of Wisconsin, Madison, Wis.
TWITCHELL, M. W., Geological Survey of New Jersey, Trenton, N. J.
ULRICH, EDWARD O., U. S. Geological Survey, Washington, D. C.
UNGER, CLAUDE E., Pottsville, Pa.
VAN DELOO, JACOB, Education Building, Albany, N. Y.
VAN INGEN, GILBERT, Princeton University, Princeton, N. J.
VAN TUYL, FRANCIS M., Colorado School of Mines, Golden, Colo.
VAUGHAN, T. WAYLAND, U. S. Geological Survey, Washington, D. C.
VOGDES, ANTHONY W., 2425 First Street, San Diego, Calif.
WAGNER, CARROLL MARSHALL, 2520 Wilshire Building, Los Angeles, Calif.
WALCOTT, CHARLES D., Smithsonian Institution, Washington, D. C.
WALLER, OTTO F., 421 Reynolds Street, Iowa City, Iowa.
WEAVER, CHARLES F., University of Washington, Seattle, Wash.
WELLER, STUART, University of Chicago, Chicago, Ill.
WHITE, DAVID, U. S. Geological Survey, Washington, D. C.
WHITTAKER, EDWARD J., Geological Survey of Canada, Ottawa, Canada.
WIELAND, G. R., Yale University, New Haven, Conn.
WILLIAMS, MERTON Y., University of British Columbia, Vancouver, B. C.
WILSON, ALICE E., Victoria Memorial Museum, Ottawa, Canada.
WILSON, HERRICK E., 224 West College Street, Oberlin, Ohio.

WINTON, W. M., Texas Christian University, Fort Worth, Texas.

WOODRING, WENDELL P., U. S. Geological Survey, Washington, D. C.

WOODFORD, ALFRED OSWALD, Pomona College, Claremont, Calif.

NEW MEMBERS

ADKINS, WALTER SCOTT, Bureau of Economic Geology, Austin, Texas.

DAREY, FRED WILLIS, Peabody Museum, Yale University, New Haven, Conn.

ELLISOR, ALVA C., Humble Oil and Refining Company, 803 Humble Building,
Houston, Texas.

GIRAUD, ANTONIO PASTOR, c/o Transcontinental de Petroleo, S. A., Tampico,
Mexico.

MCLEARN, FRANK HARRIS, Geological Survey of Canada, Ottawa, Canada.

ROMER, A. S., 422 W. 20th Street, New York City.

TIEJE, ARTHUR J., Dept. of Geology, University of Colorado, Boulder, Colo.

CORRESPONDENTS DECEASED

KOKEN, E., died November 24, 1912.

NATHORST, DR. A. C., died January 20, 1921.

WOODWARD, DR. HENRY, died September 6, 1921.

MEMBERS DECEASED

BARRELL, JOSEPH, died May 4, 1919.

BILLINGS, WALTER R., died March 1, 1920.

CALVIN, SAMUEL, died April 17, 1911.

CLARK, WILLIAM B., died July 27, 1917.

DERBY, ORVILLE A., died November 27, 1915.

DONEGHY, JOHN T., died June 29, 1921.

EASTMAN, CHARLES R., died September 27, 1918.

FONTAINE, WILLIAM M., died April 30, 1913.

GILL, THEODORE N., died September 25, 1914.

GORDON, ROBERT H., died May 10, 1910.

HAMLIN, HOMER, died in July, 1920.

HARPER, GEORGE W., died August 19, 1918.

HAWVER, J. C., died May 15, 1914.

LAMBE, LAWRENCE M., died March 12, 1919.

LYON, VICTOR W., died August 17, 1919.

MOODY, W. L., died October 9, 1920.

PROSSER, C. S., died September 11, 1916.

SEELY, HENRY M., died May 4, 1917.

WARING, CLARENCE A., died November 4, 1918.

WILLIAMS, HENRY S., died July 31, 1918.

WILLISTON, SAMUEL W., died August 30, 1918.

PROCEEDINGS OF THE FIRST¹ ANNUAL MEETING OF THE
SOCIETY OF ECONOMIC GEOLOGISTS, AMHERST, MAS-
SACHUSETTS, DECEMBER 28-30, 1921.²

SYDNEY H. BALL, *Secretary*

CONTENTS

	Page
Session of Wednesday, December 28.....	223
Election of officers for 1922.....	223
Presentation of papers.....	224
Session of Thursday, December 29.....	225
Presentation of papers.....	225
Session of Friday, December 30.....	225
Presentation of papers.....	225

SESSION OF WEDNESDAY, DECEMBER 28

The first annual meeting of the Society of Economic Geologists was held at Amherst College, Amherst, Massachusetts, on December 28 to 30, 1921, in affiliation with the Geological Society of America.

The session of Thursday was called to order by President R. A. F. Penrose, Jr.

ELECTION OF OFFICERS FOR 1922

The election of officers for 1922 was declared to have resulted as follows:

President, WALDEMAR LINDGREN

Vice-President, RALPH ARNOLD

Secretary and Treasurer, SYDNEY H. BALL, 42 Broadway,
New York City

Councilors, 1922-1923, JAMES F. KEMP and C. K. LEITH

¹ The meeting at Chicago, December 28-29, 1920, was called, by resolution of the Society, the "organization meeting"; the meeting at Amherst, therefore, becomes the first annual meeting.

² Prepared by the Secretary of the Geological Society of America from information furnished from the office of the Secretary of Economic Geologists.

The following program was then taken up:

PRESENTATION OF PAPERS

THE SOCIETY OF ECONOMIC GEOLOGISTS—ITS SPHERE AND FUTURE

PRESIDENTIAL ADDRESS BY R. A. F. PENROSE, JR.

PLAIN GEOLOGY

BY GEORGE OTIS SMITH

The paper was discussed by J. E. Spurr, Robert Anderson, L. C. Graton, A. M. Bateman, Waldemar Lindgren, and H. G. Ferguson.

GEOLOGY OF THE BRADEN MINE, CHILE

BY WALDEMAR LINDGREN AND EDSON S. BASTIN

The paper was read by the senior author and discussed by A. M. Bateman, L. C. Graton, J. E. Spurr, and others.

STRESSING ECONOMICS IN THE TEACHING OF ECONOMIC GEOLOGY

BY EDSON S. BASTIN

The paper was discussed by George Otis Smith, J. E. Spurr, and R. W. Stone.

OIL AND GAS SECTION OF THE COURSE IN ECONOMIC GEOLOGY

BY R. H. JOHNSON

EXPERIMENTAL STUDY OF THE INVASION OF OIL INTO A WATER-WET SAND

BY O. W. SKIRVIN³

Discussed by R. H. Johnson.

RESULTS OBTAINED BY IMPROVED METHODS OF EXTRACTING PETROLEUM

BY ROBERT B. BOSSLER⁴

PROBABLE ORIGIN OF CERTAIN VEIN STRUCTURES

BY L. C. GRATON

A RECENT HOT-SPRING DEPOSIT IN BOLIVIA

BY WALDEMAR LINDGREN

A SUGGESTION FOR THE TERMINOLOGY OF CERTAIN ORE DEPOSITS

BY WALDEMAR LINDGREN

³ Introduced by R. H. Johnson.

⁴ Introduced by G. H. Ashley.

SESSION OF THURSDAY, DECEMBER 29

The Society convened about 9.00 o'clock and took up the program of papers, as follows:

PRESENTATION OF PAPERS

ORE DEPOSITS OF LEADVILLE, COLORADO

BY G. F. LOUGHLIN

GOLD-BEARING CUMMINGTONITE SCHISTS OF THE BLACK HILLS, SOUTH DAKOTA

BY J. J. RUNNER⁵

Discussed by Waldemar Lindgren.

PETROGRAPHIC NOTES ON THE FRANKLIN, NEW JERSEY, ZINC ORES

BY W. C. BOWEN⁶

The paper was discussed by L. C. Graton, H. Ries, and others.

PRIMARY NATIVE SILVER ORES NEAR WICKENBURG, ARIZONA, AND THEIR BEARING ON THE GENESIS OF THE SILVER ORES OF COBALT, ONTARIO

BY E. S. BASTIN

Discussed by L. C. Graton, M. B. Baker, and A. M. Bateman.

NEED OF EXPEDITING TOPOGRAPHIC MAPPING OF THE UNITED STATES

BY F. W. DE WOLF

The paper was largely discussed, and on motion of L. C. Graton a resolution of appreciation was adopted.

SESSION OF FRIDAY, DECEMBER 30

The following program of papers was presented at the session of Friday, December 30:

PRESENTATION OF PAPERS

HAZARDS OF THE OIL INDUSTRY

BY RALPH ARNOLD

Read in abstract by Waldemar Lindgren in the absence of the author.

⁵ Introduced by E. S. Bastin.

⁶ Introduced by H. Ries.

REFLECTED HILLS IN PETROLEUM GEOLOGY

BY SIDNEY POWERS

Read in abstract by Waldemar Lindgren in the absence of the author.

STUDY OF SUPERGENE PROCESSES AT NEIHART, MONTANA

BY M. E. HURST

Discussed by J. E. Spurr, E. S. Bastin, L. C. Graton, H. G. Ferguson, G. F. Loughlin, W. A. Parks, A. F. Rogers, and A. M. Bateman.

GEOLOGICAL AND GEOGRAPHICAL OCCURRENCE OF PRECIOUS STONES

BY SYDNEY H. BALL

Read in abstract by A. M. Bateman in the absence of the author.
Discussed by G. F. Loughlin, R. W. Stone, John E. Dresser.

SOME ETCHING TESTS ON PYRRHOTITE

BY H. C. BOYDELL

Read by title in the absence of the author.

CONDITION OF MAGNESITE IN 1920

BY R. W. STONE

Discussed by E. S. Bastin, G. F. Loughlin, R. W. Stone, and A. M. Bateman.

PROCEEDINGS OF THE SECOND ANNUAL MEETING OF THE
MINERALOGICAL SOCIETY OF AMERICA, HELD AT AM-
HERST, MASSACHUSETTS, DECEMBER 29, 1921.¹

HERBERT P. WHITLOCK, *Secretary*

CONTENTS

	Page
Session of Thursday, December 29, 1921.....	227
Election of officers for 1922.....	227
Report of the Secretary.....	228
Report of the Treasurer.....	228
Report of the Editor.....	228
Report of the Committee on Nomenclature and Classification of Min- erals.....	228
Presentation of papers.....	229

SESSION OF THURSDAY, DECEMBER 29, 1921

The Mineralogical Society of America held its second annual meeting at Amherst College, Amherst, Massachusetts, on December 29, 1921, in affiliation with the Geological Society of America.

In the absence of the President and Vice-President, Dr. Edgar T. Wherry presided.

On motion of the Secretary, the reading of the minutes of the last annual meeting was dispensed with, in view of the fact that they have been printed in volume 6, number 2, of the *American Mineralogist*.

ELECTION OF OFFICERS FOR 1922

The Secretary announced that sixty ballots had been cast for the officers for 1922 as nominated by the Council, and that the list was elected. It is as follows:

President, THOMAS L. WALKER

University of Toronto, Toronto, Canada

Vice-President, FREDERICK A. CANFIELD

Dover, New Jersey

¹ Manuscript received by the Secretary of the Society March 8, 1922.

Secretary, HERBERT P. WHITLOCK

American Museum of Natural History, New York City

Treasurer, ALBERT B. PECK

University of Michigan, Detroit, Michigan

Editor, WALTER F. HUNT

University of Michigan, Detroit, Michigan

Councilor, THOMAS L. WATSON, 1922-1925

University of Virginia, Charlottesville, Virginia

REPORT OF THE SECRETARY

The Secretary reported that the roll of the Society now comprised 67 Fellows and 159 members, a gain of 5 Fellows and 28 members for the year.

REPORT OF THE TREASURER

The report of the Treasurer was read in abstract by Dr. E. H. Kraus.

On motion by Dr. Kraus, an Auditing Committee, consisting of Dr. A. S. Eakle and Prof. Ellis Thomson, was appointed by the chair. This committee, at the afternoon session, at 2 o'clock, reported that the Treasurer's report was correct.

REPORT OF THE EDITOR

The Editor reported that the proceedings of the meeting, several papers, and abstracts of others had been published in the *American Mineralogist* during the year 1921.

Then followed a discussion of the subject of continuing the printing of abstracts in the *American Mineralogist*, in the course of which several Fellows emphasized the need of book reviews and shortened abstracts.

On motion of Dr. E. H. Kraus, a vote of appreciation was tendered to Dr. Edgar T. Wherry for his services as Editor.

REPORT OF THE COMMITTEE ON NOMENCLATURE AND CLASSIFICATION OF MINERALS

The report of the Committee on Nomenclature and Classification of Minerals was read in abstract and was received as a report of progress.

On motion of Professor Watson, it was voted to issue this report to members of the Society for criticism and comment.

PRESENTATION OF PAPERS

The presentation of scientific papers was then taken up as follows, according to the program:

*SOME PROBLEMS OF MINERAL GENESIS IN SOUTH AFRICA*¹

PRESIDENTIAL ADDRESS BY CHARLES PALACHE

A STUDY OF CRYSTAL SYMMETRY

BY AUSTIN F. ROGERS

LATENT MEROSYMMETRY

BY EDGAR T. WHERRY

*USE OF PLANS AND ELEVATIONS IN TEACHING GEOMETRICAL
CRYSTALLOGRAPHY*

BY AUSTIN F. ROGERS

PLEA FOR ECONOMIC MINERALOGY

BY OLIVER BOWLES

CÆRULEOFIBRITE, A NEW MINERAL

BY EDWARD T. HOLDEN

CROCIDOLITE FROM EASTERN PENNSYLVANIA

BY EDGAR T. WHERRY AND EARL V. SHANNON

OCCURRENCE OF MONOSULPHIDE OF IRON

BY ARTHUR S. EAKLE

CRYSTALLOGRAPHY OF THREE RHODE ISLAND MINERALS

BY A. C. HAWKINS

MINERALOGY FOR STUDENTS OF DENTISTRY

BY E. H. KRAUS

WHITE CHLORITE FROM EASTERN PENNSYLVANIA

BY EDGAR T. WHERRY AND EARL V. SHANNON

JADES OF MIDDLE AMERICA

BY HENRY S. WASHINGTON

¹ Read by Edgar T. Wherry in the absence of President Palache.

*ANALCITE FROM NOVA SCOTIA, WITH A DISCUSSION OF ANALCITE ANALYSES
IN GENERAL*

BY A. L. PARSONS

SILICATES OF THE CONTACT LIMESTONES OF CRESTMORE, CALIFORNIA

BY ARTHUR S. EAKLE

TWO CORRECTIONS TO MINERAL DATA

BY N. L. BOWEN

NEW SOURCE OF MONOCHROMATIC LIGHT

BY ALBERT B. PECK

CARE OF MUSEUM SPECIMENS

BY A. L. PARSONS

INDEX MINERALS FOR THE INTERPRETATION OF GEOLOGICAL HISTORY

BY J. J. RUNNER

AFTER-EFFECTS OF IGNEOUS INTRUSION ¹

PRESIDENTIAL ADDRESS BY JAMES F. KEMP

(Read before the Society December 28, 1921)

CONTENTS

	Page
Development of microscopic petrography in the last fifty years.....	231
After-effects of igneous intrusion.....	232
Frequency of the unexpected discovery of igneous rocks.....	233
Mineralizers remaining in crystallized igneous rocks.....	234
Eviction of mineralizers from a crystallizing magma.....	235
After-effects in crystallized igneous rocks.....	236
Reaction rims and related phenomena—deuterics.....	236
Xenoliths, more or less digested.....	237
Orbicular granites.....	237
Actual analyses of escaping gases at volcanic vents... ..	238
Kilauea, by Day and Shepherd.....	238
Katmai, by Allen and Zies.....	239
Compilations by F. C. Lincoln.....	239
Comparison of effusive emissions with those of intrusive rocks.....	240
Interpretation of Precambrian impregnated strata.....	241
Contact zones, especially from limestones.....	243
Mineral veins.....	245
Igneous after-effects.....	245
Exaggerated estimates of meteoric ground-waters.....	246
Magmatic emissions as producers of veins... ..	247
Water in solid solution in pitchstones.....	248
Conclusion.....	249
References.....	250

DEVELOPMENT OF MICROSCOPIC PETROGRAPHY IN THE LAST FIFTY YEARS

A backward look over the course of geologic thought and interest in North America during the life of our Society, and perhaps for ten or fifteen years earlier, brings into the foreground some striking features. A span of years of this duration is not beyond the personal recollections

¹ Manuscript received by the Secretary of the Society January 17, 1922.

of some of the Fellowship and not beyond the personal participation of a few who are still active. One recognizes at once the entrance into general use of the polarizing microscope and the consequent widespread study of rocks in thin sections. Although this method of investigation was cultivated in this country in the decade of the seventies by A. A. Julien, C. E. Wright, E. S. Dana, J. H. Caswell, George W. Hawes, B. K. Emerson, M. E. Wadsworth, and perhaps one or two others; and although stimulated by Zirkel's volume in the Reports of the Survey of the Fortieth Parallel, by Hawes' invaluable descriptions of the rocks of New Hampshire, and by Caswell's beautifully illustrated pages on the rich soda rocks of the Black Hills, the early years of the next decade saw the greatest impetus to American petrography.

Whitman Cross, J. P. Iddings, J. S. Diller, F. D. Adams, George H. Williams, J. E. Wolff, and one or two more, all returned from European study fired with ideals and ambitions gained in the laboratories of Zirkel or Rosenbusch. George H. Williams became the preeminent teacher, and his contagious enthusiasm, clear presentation, and temperament of the artist in his work inspired great zeal in many younger men who sat in his lecture-room or wrought in his laboratory. I think we may truthfully say that the work of the men mentioned, of others who came later, and of contemporaries abroad has rounded out the descriptive part of the branch of geology which deals with the igneous and metamorphic rocks. We are not likely to discover anything further which is very essential regarding components and structures. The actual facts are well and completely recorded and lengthy papers elaborately descriptive of details are not able to add much to the general stock of knowledge. They have become wearisome and of slight value. With the sediments the case is different. Long neglected, they are now gaining recognition, and for some years we are likely to learn much that is new and significant concerning the minute mineralogy of the clastic and organic rocks. With all the rocks, description has largely given way to interpretation, petrography has become petrology, and the possibilities of fundamental advances in our understanding of processes are now looming large.

AFTER-EFFECTS OF IGNEOUS INTRUSION

Another subject, impressive in the importance which it has been gaining in just about the three decades covered by the life of our Society, is that which involves the after-effects of igneous intrusion, and it is to a survey of these processes and results that I wish to direct your attention. They are fruitful ones and are large with the promise of clearing up

much which has puzzled our contemporaries and our predecessors. They begin when an uprising molten mass stops and crystallizes; they cease only when its emissions and its stores of excess heat as compared with its wall-rocks are exhausted.

FREQUENCY OF THE UNEXPECTED DISCOVERY OF IGNEOUS ROCKS

At the outset let me remind you that we are never safe from igneous rocks. No matter how undisturbed sedimentary strata may appear, the geologist would be rash who would dismiss the possibility of a dike or neck, or even of a deep-seated mass. A few illustrations will suffice. Among the older strata one might think of the almost undisturbed Paleozoic formations of central New York as most unlikely scenes of igneous action, but from accumulated observations extending over nearly a century we now know of the alnoite and mica-peridotite dikes which begin in the faulted Trenton at Manheim Bridge,¹ near Utica; appear in the Salina at Geddes and Syracuse;² pierce the Devonian north and south of Ithaca;³ cut the Monongahela series of the Coal Measures in the Connells-ville basin of western Pennsylvania;⁴ and outcrop at intervals across Kentucky⁵ and Arkansas⁶ in strata of the reverse and descending order of age. While the dikes may not all belong to the same time of outbreak, there is a striking similarity in their mineralogy.

Now, even a small dike implies a much larger reservoir in depth. It follows that these intrusives, so closely similar in petrographic character, are in all probability the most basic and most fluid differentiates of a vast and widely distributed series of related magmas. If not all, at least one of the magmas forced its way upward at a time appreciably later than the age of the latest strata cut—that is, than the Monongahela series of the Pennsylvanian. How much later we have no direct means of knowing, but in the Connellsville coal basin the dike has extensively coked the Pittsburgh seam. If we are justified in the inference that this seam was coking bituminous coal when the dike entered, then we have to allow a long time to have elapsed before the original peat could have reached this stage.

There is not very much, if any, good coking coal the world over of Tertiary age, in gently folded strata, uninfluenced by intrusive rocks. We seem to need a longer period of time than the Tertiary to bring about these changes; and, on the assumption that the Pittsburgh seam was coking coal when the dike came in, we are forced to place the time of intrusion at least one long geological period after the close of the Pennsylvanian. It may have been several. We may shorten the assumed time

by just so much as we attribute to an intrusive dike the power to coke tightly confined and compressed lignite; but the more one reflects on the matter, the more one is inclined to allow a goodly stretch of geologic time. Will the Permian suffice, so that the dikes were coincident with Appalachian upheavals? Are the parent magmas more western relatives of the post-Carboniferous granites of Rhode Island and Connecticut? Are they western representatives of the magmas which yielded the extensive late or post-Jurassic diabases of the Atlantic coastal region? Are they in any way related to the intrusives of Cretaceous age, which are best developed in the syenite magmas of Arkansas? These are questions more easy to ask than to answer; but one can not avoid reflecting on the powerful heat agents which may have affected, since the close of the Carboniferous, the lower strata in the localities mentioned.

Again one might cite the flat beds of the Coastal Plain around the Gulf of Mexico, penetrated, as they are, by basaltic plugs and stocks near Tampico,⁷ and raise the question as to the parent reservoirs and their depths. Even in Texas and Louisiana our reasoning about the salt domes and their attendant sulphur-bearing caps of limestone and anhydrite seems unable to bar out altogether subterranean intrusive masses. Last winter, at the Chicago meeting of the Society, when we heard the interesting paper of Dr. W. H. Bucher,⁸ in which he described the centrally eroded and steeply, outwardly dipping dome in Adams County, on the Ohio River, in Ohio, and the parallel drawn by the author with similar phenomena near Steinheim, Würtemberg, we could not help contemplating the possibility that beneath this upheaval a laccolith might lie concealed. I repeat, that we are never safe from igneous rocks, at no vast depths, no matter how innocent flat strata look at the surface.

MINERALIZERS REMAINING IN CRYSTALLIZED IGNEOUS ROCKS

Observation and interpretation have now built up a widespread and generally accepted conception of the process of crystallization in an intrusive mass which has practically finished its upward journey from the depths. In great detail and in such grades of accuracy as we may readily judge under the guidance of our fellow-member, Henry S. Washington,⁹ our well-nigh innumerable analyses show us what are the chemical compositions of the chilled and cold results of crystallization. But we all know that these are but a part of the story. All magmas contain dissolved gases which we technically call mineralizers. Traces of them remain even in cold, hard, crystallized end-products, and regarding the composition and amounts of the traces we have the valuable paper of

Rollin S. Chamberlin.¹⁰ But the vast proportion of the gases escape during crystallization.

While yet dissolved or involved in the magmas, the mineralizers exert an important influence on the fusing point and doubtless tend to lower it very greatly from the high temperatures required for unmineralized melts. Experiment in the laboratory and observation in the field convince us that, in general, high silica magmas are richest in dissolved gases, and basic ones less rich. A survey of known occurrences leads to the conclusion that the magmas of the composition of grano-diorite—that is, the ones intermediate between true granites and quartz-diorites and shading into each—are probably the most widespread and greatest contributors of these end-products on crystallizing. True granites are also generous givers, as are the monzonites, intermediate between syenites and diorites. In Brögger's classic region around Christiania, high soda rocks have been potent developers of pegmatites¹¹ and must have been richly charged with mineralizers. As we go down the scale of silica content, mineralizers seem to wane in importance, until we reach the peridotites. In them, however, if we are correct in our growing inference that the hydrogen and oxygen in the so-called water or hydroxyl required for serpentinization are of magmatic origin, and that the hydration followed as an after-effect of crystallization, then the peridotite magmas now represented by serpentine must have been richly charged with the elements of water.

The general disposition of students of the subject is to consider the mineralizers normal components of deep-seated magmas and to be as much a part of them as the better-known silica and the common bases. Few, if any, who have given the matter thought believe that the involution of sea-water into these molten masses is physically possible. We may admit, however, that, in so far as the upward moving and possibly superheated mass melts into itself and absorbs rocks with minerals such as serpentine or kaolinite, with combined hydrogen and oxygen not easily driven off, the content of mineralizers in the intrusive magma may be increased.

EVICION OF MINERALIZERS FROM A CRYSTALLIZING MAGMA

As a general rule, we are all well aware that cooling magmas crystallize in largest part into anhydrous minerals, which lack the peculiar elements of the mineralizers. A sweeping statement can not be made, because we do know that hornblendes carry a half per cent or less of hydroxyl; that many micas have hydrogen and fluorine; that apatite,

"the Jack in every alley" among the igneous rocks, has chlorine or fluorine; that the sodalite group has chlorine and the noselite group the sulphuric acid radicle; so that a little of the mineralizers may remain in the composition of some characteristic but subordinate igneous rock-making minerals. The great proportion of the igneous rock-makers are practically devoid of them, certainly so far as notable percentages go. We therefore conclude that the process of crystallization is a process of eviction, and that with the advance of solidification nearly all the dissolved gases are gradually left uncombined. They are evicted first from the cooling and consolidating exterior of a batholith or laccolith. As crystallization extends inward and downward, they continue to be freed, since we do not find them in the congealed mass, except as mentioned above. They doubtless escape through crevices in the shell, very probably along trunk channels, and pass into or through the wall-rocks, much more abundantly at some places than at others.

This conception appeals to me rather more strongly than the one recently stated by our lamented fellow-member, Joseph Barrell,¹² in which an advance guard of escaped or escaping mineralizers is believed to precede the upward course of the molten mass. Possibly no sharp line can be drawn between the two views. In a matter so largely speculative, one may hold opinions or beliefs in a plastic state; but in the discussion of the subject in the present paper the point of view will be held that the mineralizers and their dissolved burdens are evicted and escape on consolidation of the parent magma.

AFTER-EFFECTS IN CRYSTALLIZED IGNEOUS ROCKS

REACTION RIMS AND RELATED PHENOMENA—DEUTERICS

Perhaps the very earliest of the "after-effects" may be observed in the intrusive itself. The microscope has often revealed to us the reaction rims which are developed in the gabbros and more basic rocks. Zones or crowns or aureoles of minerals of intermediate composition are found between feldspars on the one side and magnetite, pyroxene, or some other basic component on the other. Garnet, hypersthene, and biotite are very frequent in the rims, and a zone of untwinned feldspar, clear and colorless, may be often seen.¹³

Again, in the diabases and gabbros we sometimes note brown biotite along the contact of magnetite and bordering feldspar. J. J. Sederholm described years ago peculiar micro-pegmatitic intergrowths of vermicular quartz and plagioclase fringing larger feldspar nuclei in granites and gneisses. He called the intergrowth myrmekite.¹⁴ All the minerals of

these border zones he has grouped more recently as synantetic minerals, or those formed where two older minerals meet. These reactions of the very closing stages of crystallization and dependent on its mineralizers, or "juice," Sederholm proposes to call deuteric¹⁵—that is, they are second or subsequent in development to crystallization proper. The results are far more widely spread than petrographers have generally realized, and once the observer's eye is quickened to note them, they will be frequently detected. In some of our petrographic laboratories one may now hear deuteric from every one's tongue as soon as questions come up which affect the *interpretation* of what we actually see in the thin sections.

XENOLITHS, MORE OR LESS DIGESTED

Before we pass to the effects on the wall-rocks by the emissions, I may mention one or two others which come to pass within the consolidating rock-mass itself. The wall-rocks make contributions to the intrusive in the form of fragments caught up when the magma stopes its way upward, as we say, adopting the miner's term. While these xenoliths, in stages of greater or less reorganization, are very frequent phenomena in many igneous masses and may or may not display evidence of corrosion, recrystallization, and saturation, there are two or three varieties specially worthy of remark.

ORBICULAR GRANITES

All students of the igneous rocks are familiar with the curious phases of the intrusive varieties which are known as orbicular or spheroidal granites, or diorites, or gabbros, as the case may be. Stockholm is, perhaps, the most accessible locality, but others are well known in Finland, Ireland, Corsica, Sardinia, and elsewhere in Europe. In North America boulders of excellent development have been discovered in Rhode Island¹⁶ and in the lower peninsula of Michigan.¹⁷ During the International Geological Congress in Stockholm, in 1910, some of the delegates were taken on an excursion to a granite quarry in the city, where the orbicular granite was exposed. Discussions on the spot led to the conclusion that the orbicular structures could be best explained by the digestion of fragments from some wall-rock. Centers of abnormal composition were thereby established around which, after the absorption of the inclusions, recrystallization into the spheroids resulted. Our Michigan case gives evidence of associated processes allied to the formation of pegmatites. In any event, the peculiar and striking structures are difficult to explain without the aid of deuteric agencies.

Even when the recrystallization does not go so far, one may trace in some granites an extraordinarily progressive series, from inclusions of schists, angular and not much changed, through others charged with granitic minerals, on through still others, the mere outlines and ghosts of their former selves, until only a few shreds and basic streaks of biotite remain. The Stony Creek granite of Connecticut,¹⁸ taken from quarries a few miles east of New Haven, is at times very prolific in these phenomena. The foundations and lower courses of the buildings of Columbia University display in the cut blocks extremely instructive illustrations.

As remarked, the xenoliths caught up in granite and related intrusives are often sharp in their outlines and show no absorption of their substance by the inclosing magma. When they were captured the magma was probably cold enough to be near the point of consolidation. Such xenoliths, however, have sometimes produced an effect on the magma analogous to catalyzers, or stimulants of reactions, although not themselves affected. One may observe strongly pegmatitic developments harbored, so to speak, in the lee of the inclusions, as if the mineralizers had gathered next them and had brought to pass localized and very coarse crystallizations. This pegmatitic phase may contain coarse magnetite, tourmaline, and rarer minerals, all characteristic of the work of mineralizers.

ACTUAL ANALYSES OF ESCAPING GASES AT VOLCANIC VENTS

KILAUEA, BY DAY AND SHEPHERD

I may next raise the question, How much do we know regarding the actual composition of the emissions? In so far as effusive rocks are trustworthy representatives of deep-seated intrusives, we may cite the actual analyses of escaping gases. The best and most carefully made determinations which have been published as yet are those of Day and Shepherd,¹⁹ from the basaltic magmas of Kilauea. Water, escaping as a gas and caught and condensed as a liquid, was the most abundant emission. It was followed by carbon dioxide, nitrogen, hydrogen, carbon monoxide, and sulphur dioxide. Dissolved in the water, which was condensed in the tubes, were fluorine, sulphur trioxide, chlorine, and in one sample a very little ammonia. There were also the common bases of the igneous rocks—soda, potash, lime, ferric oxide, alumina, and in one sample a questionable trace of titanium dioxide. No silica is reported, and the authors remark that the bases might have been derived from the glass of the conductors and condensers.

KATMAI, BY ALLEN AND ZIES

In the Katmai region of Alaska the enormous development of fumaroles following the great explosive outbreak of June, 1912, has even suggested for one district the appropriate name "The Valley of Ten Thousand Smokes."²⁰ As part of the work of the expeditions supported by the National Geographic Society, samples of the emissions were taken by J. W. Shipley in 1917 and by E. T. Allen and E. G. Zies in 1919. The analyses have been made in the Geophysical Laboratory in Washington, and by the great kindness of Doctors Allen and Zies I am permitted to summarize them in advance of publication. All the percentages are in volumes. Steam is overwhelmingly the most abundant, and in the average of fifteen samples was 99.81 per cent. In the highest sample it is 99.99; in the lowest, 98.6. The average of the total fixed gases is naturally 0.19 per cent, and in the fifteen the highest is also naturally 1.4 per cent and the lowest 0.01 per cent. In order of abundance we have in the average, expressed in percentages, carbon dioxide, 0.106 (maximum, 0.986; minimum, 0.003); nitrogen and argon, .043 (maximum, 0.268; minimum, 0.002); hydrogen sulphide and hydrogen, 0.024 (maximum, 0.051; minimum, 0.002); methane, 0.016 (maximum, 0.169; minimum, 0.001); oxygen, 0.002 (maximum, 0.083; minimum, 0.001). One determination gave carbon monoxide 0.008.

In a series of twenty samples, taken in 1917 by J. R. Shipley, dissolved gases were caught in a barium hydroxide train, so as to give the following volume percentages: hydrochloric acid—average, 0.117 (maximum, 0.566; minimum, 0.006); hydrofluoric acid—average, 0.032 (maximum, 0.099; minimum, 0.003); hydrogen sulphide—average, 0.029 (maximum, 0.095; minimum, 0.0007). These determinations are of especial interest when used in the interpretation of emissions from intrusives, because they show three of the mineralizers with which we necessarily have a great deal to do. I am, therefore, especially indebted to Messrs. Allen and Zies for the advance records.

COMPILATIONS BY F. C. LINCOLN

It is interesting to compare with the results just summarized the earlier information made available in 1907 by F. C. Lincoln,²¹ at the time one of my graduate students. Doctor Lincoln compiled all the accessible analyses of volcanic emissions, about two hundred in number. From these he selected fifty, regarded as both typical and reliable. After discussing the probabilities of the admixture of air with the samples and allowing for its influence on the computed averages, Doctor Lincoln

reached the general conclusion that, aside from water gas, carbon dioxide is the most abundant; nitrogen follows next; then the sulphurous gases, hydrogen sulphide and sulphur dioxide, the former several times as abundant as the latter; next, hydrochloric acid, hydrogen, methane, and a trace of ethane. Except the water gas, which I mentioned in a preliminary way to prevent misunderstanding, the above are not condensable at ordinary temperatures and pressures. Under the head of condensables come sulphur, salt, salammoniac, and ferric chloride. Gypsum is associated, but is doubtless a result of a surface reaction. A long series of other elements and compounds have been here and there reported—tellurium, arsenical compounds, boric acid, sulphates of several kinds, and all the common economic metals except gold and silver. All these will have significance when we come to speak of the last stages of after-effects.

COMPARISON OF EFFUSIVE EMISSIONS WITH THOSE OF INTRUSIVE ROCKS

As compared with the products from intrusive rocks, the most important one which is lacking is silicon or silica. Silica must fail to pass off with escaping gases at the temperatures and pressures of the surface, but it goes freely into solution at lower temperatures in alkaline or other waters, as the abundant siliceous sinters around hot springs demonstrate. Under deep-seated conditions, as a fluoride or related compound, silicon may escape at high temperatures. With falling temperatures and the existence of liquid water, silica unquestionably passes outward in great quantity, as will be subsequently brought out in speaking of contact zones and mineral veins. These actual determinations of the mineralizers were of necessity made on the emissions of effusive rocks. The samples are caught at the surface and as they escape into the atmosphere. The substances dissolved in the water obtained in this way by condensing dissociated hydrogen and oxygen, or steam, are only a partial indication of what takes place around a deep-seated intrusive, under the high temperatures and pressures attending a cooling and crystallizing magma and under the precipitating influence of the oft-times active chemical reagents in the surrounding wall-rocks. We must learn of these processes by the careful interpretation of their results. Several of the most significant I wish to pass in brief review, and first the impregnated ancient strata which have been studied and in later years interpreted in almost all the Precambrian areas of the world.

INTERPRETATION OF PRECAMBRIAN IMPREGNATED STRATA

The great fact which stands out from the results of this study, and which we are now finding in practically all the later work, is the recognition of one or more very ancient series of strata, as distinct from intrusive granite. Sometimes they are undoubtedly sedimentary and contain limestones, quartzites, and thinly laminated gneisses or schists which represent ancient shales. The Grenville of eastern Canada, of the Adirondacks, of the Highlands of the Hudson and New Jersey, and probably of southeastern Pennsylvania, Maryland, and Delaware, is a familiar illustration. Here and there, not too greatly altered members are easily recognized to be sediments; but with them are mixed rocks, the "migmatites" of the Scandinavians, which have first been considered excessively metamorphosed sediments; then extremely variable igneous rocks; and finally, and probably correctly, original sedimentary deposits penetrated, soaked, and altered by the so-called "juice of the magma." The juice carried with it into the surrounding rocks the elements of many silicates and, penetrating especially along bedding planes or planes of schistosity, introduced pegmatitic matter far and wide.

These or similar changes did not entirely escape the keen observation of early workers. All will recall the quaint diagrams in the early textbooks, which picture the ancient metamorphic strata resting on the underlying granites, from which pegmatite and other dikes wriggle their way upward and outward. Élie de Beaumont, Michel-Levy, and other French observers mention frequently "agents mineralisateurs," or, as we say, "mineralizers."

In later years French observers began to speak of *lit-par-lit* injection—a phrase which we especially owe to F. D. Adams for its introduction into North American usage. I need only to remind you of the extraordinarily suggestive monograph of Adams and Barlow²² on the Haliburton and Bancroft area of Ontario, and the interesting way in which the former traced out the entrance of silica, probably with some bases, along the bedding planes of limestones; the *lit-par-lit* production of feather amphibolites; and finally the reorganization of the limestone into amphibolite itself. Adirondack workers became familiar with mixed rocks. In one place we met gneissoid members of general syenitic composition, but with blue labradorite augen, which must have come from neighboring anorthosite. Elsewhere amphibolites with the same blue augen; again, gneissoid granitic members with long, thin streaks of amphibolite ranged in notably parallel grouping; in still other exposures, bedlike masses of magnetite folded like sediments, but in wall-rocks indistinguishable from familiar

intrusives. In southeastern New York the very ancient Fordham gneiss was of such variable character that earlier observers scarcely knew whether it was igneous or sedimentary. The extended and careful studies of my colleague, Charles P. Berkey, have shown it to be both, or rather an ancient sediment soaked and rearranged into a mixed rock by contributions from the near-by granites. In the neighboring parts of New Jersey, J. E. Wolff had outlined the same history for the Pochuck gneiss,^{22a} the probable equivalent, as we now believe, of the Fordham. C. N. Fenner traced from the Pompton granite the same influence on neighboring foliated rocks.^{22b}

Recently, in a posthumous paper from our late fellow-member, Joseph Barrell,¹² a paper to which I have made reference above, the influence of intrusive masses has been demonstrated in southern New England, in localities where hitherto the strata have been regarded as regionally metamorphosed and as brought to their present state without the necessary aid of igneous rocks. In discussing the mineralogical results, the author utilizes the later results of physical chemistry.

The invaluable excursions and discussions made possible by the International Geological Congress in Stockholm in 1910 gave visitors from this side of the ocean the privilege of seeing similar phenomena in Sweden. We heard at first hand the older views from Törnebohm, and the later interpretations from Högböhm and Holmquist, with comments from Sederholm, of Finland. With the remarkable work of the Geological Survey of Finland, under Doctor Sederholm, Precambrian workers the world over are now familiar and from it have gained much help.

As the net result of all these observations and interpretations and from the work of others whom I can not mention in detail, we are now well assured that uprising igneous magmas are often charged with mineralizers which have been later freed in the process of crystallization and have carried great quantities of dissolved matter into surrounding older wall-rocks, usually of sedimentary origin. The mineralizers have so profoundly affected the wall-rocks that first one set of observers have thought them igneous, and then another set sedimentary. The modern student now recognizes them as both, and is sometimes unable to draw a sharp line as to just where original sedimentary matter ends and contributions from the intrusive begin. At points remote from the intrusive we find augen or minute lenses of pegmatitic matter. Nearer the apparent source the injections become larger and may afford the so-called "segregated veins" of the older geologists. When such phenomena now confront us we promptly look around for the intrusive mass of granite or related rock which has caused the lit-par-lit injections. Where the intrusive was

richly charged with mineralizers we may even observe toward the contact such thoroughly reorganized and richly and porphyritically charged schist that this border rock has itself been called a porphyritic granite.

CONTACT ZONES, ESPECIALLY FROM LIMESTONES

Closely akin to the lit-par-lit injections and the reorganization of large masses of older wall-rock throughout impressive distances from the igneous source are the phenomena distinctively called contact zones. They are portions of the wall-rock adjacent to an intrusive which are so deeply affected by its influence and by its contributions as to be recrystallized often into entirely new minerals. When the wall-rocks are older igneous varieties or quartzose sandstones, but little may be produced in the way of changes. When they are shales or slates, our familiar hornfelses result, often with andalusite, variety chiastolite; often with biotite, sillimanite, staurolite, plagioclase, and occasional garnets. All stages may be traced, from sedimentary beginnings of chiastolites, showing little more than assemblages of carbonaceous pigment, to the beautifully developed, finger-shaped crystals with their included crosses. Since all the chemical components for the chiastolites and other aluminous silicates are in the shales or slates, there is no occasion to assume necessary contributions from the intrusive rock. But when we come to limestones the case is different. We now deal with some of the most interesting phenomena in the wide range of geology and with the most prolific mineral localities of the world. Over the large part of the areas affected the limestones are, perhaps, changed to crystalline marble, but locally and often for long distances outward they are entirely or in large part recrystallized to lime silicates, of which diopside, wollastonite, garnet, epidote, vesuvianite, and the scapolite group are most frequent and most abundant.

Quite naturally the earlier view reached by observers was that the lime silicates only resulted when the original limestone contained silica and alumina in such quantity as to furnish the raw materials for the later formed minerals. Heat, pressure, and the help of hot waters from the intrusive were then deemed sufficient to cause the recombinations. If we start with calcium carbonate, silica as quartz or chert, kaolinite, and, in subordinate degree, ferric hydrate or siderite in the limestone, and end with lime silicates, alumina silicates, and minor iron silicates in the contact rock, carbon dioxide and water have to depart.

One of the most ingenious and interesting of the early papers of Joseph Barrell is his discussion of the "Physical effects of contact metamorphism,"^{22c} wherein, by using percentages by volume instead of by weight,

he drew the conclusion that voids would result equal to 29.7 per cent for iron epidote, and 46.9 per cent for grossularite. When, however, early in 1905, it was almost simultaneously announced by Professor Lindgren,²³ from his observations in Morenci, Arizona, and myself from studies in San José, Tamaulipas, Mexico,²⁴ that much or almost all of the supposed grossularite or lime-alumina garnet of the zones was really andradite, the lime-iron variety, it became practically impossible to believe that so much iron oxide had ever been originally in the limestone. When, moreover, we realized the great size of associated bodies of magnetite and specular hematite, the case was even stronger. There are not a few great bodies of iron ore of this kind in the Cordilleran region; in fact, practically all the iron ore thus far discovered in the West is on the contact of intrusive rock and limestone. Besides the iron silicates and oxides, we have great bodies of iron sulphide, sometimes with copper associated, sometimes with other ores. The conclusion is irresistible that, from the cooling and crystallizing intrusive mass, iron and other metalliferous salts, along with silica, have been fed into the limestone wall-rock in vast quantities and have produced alike the lime-silicate zones, the ore bodies of intergrown magnetite and specular hematite, and the various sulphides.

Some interesting reasoning has been carried out as to the form of iron compound which was primarily yielded by the intrusive. Experience around volcanic vents leads us at once to suspect ferrous or ferric chlorides. The suggestion of iron haloid compounds was made by J. H. L. Vogt in the last century, but the haloid compounds are rejected as a serious factor in his joint text-book with Beyschlag and Krusch in 1910.²⁵ Iron carbonate in the presence of water finds greater favor.

Leith and Harder, in their studies of the Iron Springs District of southwestern Utah,²⁶ in 1908 write a reaction using ferrous chloride in association with calcium carbonate and derive specularite. V. M. Goldschmidt, describing in 1910 the zones near Christiania, Norway,²⁷ looks with favor on iron chloride and fluoride and gives a reaction of ferrous fluoride and calcium carbonate for specularite, believing also in the possibility of magnetite. In explaining zinc-blende deposits at the contacts, zinc chloride is tentatively considered by Doctor Goldschmidt.

All these speculative attempts to throw light on the chemistry of the process find support in the demonstrated presence of hydrochloric acid, common salt, salammuniac, and hydrofluoric acid in the analyses of emissions from effusive sources.

With respect to the silica, one would at once surmise haloid compounds as well as forms of silicic acid. Its actual introduction from the igneous

source, together with that of iron and minor elements, is proven both by the absence of the cavities, which we would infer from the recrystallization of earthy limestones, and by the absence of the silica and iron in analyses of what seem to be representative samples of unaltered limestone.²⁸ Tests of the latter character have been made by Waldemar Lindgren, on a very elaborate scale, in the mines at Carr Fork of Bingham Canyon, Utah. Samples taken by channeling across hundreds of feet of exposures in the cross-cuts, when analyzed, showed that the metamorphosed limestone had a decided excess over the unchanged prolongation of the same stratum. The results were reported to the National Academy of Sciences in May, 1920, but will ultimately appear in detail.

Observations by one of my old students, the late Prof. Charles A. Stewart,²⁹ of the University of Idaho, led us years ago to the conclusion that the silica and iron for the garnets must penetrate at times the minutest pores of the calcite in the limestone and develop small, isolated garnets having no visible connection with supply cracks or with larger masses.

The study of contact zones has been especially stimulated in later years, because they are so often the locus of ore deposits. The mining operations undertaken along them have enormously facilitated and extended our opportunities for study. Earlier observers walked over the more or less weathered surface exposures. Later observers follow the phenomena underground, it may be through many miles of drifts and cross-cuts. In most localities observers concluded that the lime silicates are the first effects in time. Next follow the magnetite-specularite bodies of iron ore, often of huge size, seldom entirely failing as scattered minerals. The almost universal veinlets of sulphides of iron, copper, and less often of other metals, which cut across the silicates and the iron ores, come third.²⁸ In one or two cases other observers have thought that the iron ores preceded the lime silicates. Among the lime silicates we may note in instances that garnet, epidote, and vesuvianite favor positions next or near the intrusive; farther away, wollastonite and diopside predominate, gradually giving way to marble, which itself fails by interfingering passages to unaltered limestone.

MINERAL VEINS

IGNEOUS AFTER-EFFECTS

Frequent reference has been earlier made in this address to pegmatites. I may remind you that geologists have been long of two minds, whether to speak of pegmatites as dikes or veins. Some have compromised with

the adjective aqueo-igneous. That igneous vapors or mineralizers were of moment in their formation has been long recognized. Except as the home of cassiterite, the common ore of tin, however, typical pegmatites were not often productive of ores in earlier years and were not given much attention by mining geologists. With the increasing use of tungsten, molybdenum, and the rare earths, the pegmatite veins or dikes have been of growing significance in their bearing on our interpretations of vein phenomena.

If we go back to the year when our Society was organized, we find not only pegmatites, but igneous after-effects in general, receiving slight attention in the study of veins. Beginning, however, in the early nineties and parallel with the spread of petrography, we find them both increasing in favor.

I have no time to trace in detail the very interesting chapter in the history of geology which is based on the earlier contributions to this branch of geologic thought. The chapter covers the last decade of the past century and the first one of the present. Its documentary records largely consist of the writings of J. H. L. Vogt in Norway,³⁰ and of the distinctive American school of younger men, who were gradually breaking away from the views of their elders, from the teachings of their youth, and who were striking out into new fields of thought and interpretation. As one follows through the successive papers of W. Lindgren, J. E. Spurr, and myself as three among the earlier ones who awakened to the dawn of a new era, the growing faith in the intrusive rocks and their after-effects comes out very strongly. Rather cautiously adopted at first, we find the converts growing bolder, until a paper was written by myself in 1901 whose object was to prove not only that igneous after-effects were more reasonable explanations for most of our veins, but that we then knew enough about the absence of meteoric ground-waters in our increasing number of deep mines and deep bore-holes to show that nothing else than magmatic waters would reasonably answer.³¹

EXAGGERATED ESTIMATES OF METEORIC GROUND-WATERS

The subsequent shrinkage in the amount of meteoric waters believed to exist within the crust is most impressive. Before 1900 the most frequently cited estimate was that of Achille Delesse, in 1861,³² that the ground-waters, if brought to the surface and distributed uniformly over the earth, would yield a layer 7,500 feet deep. In 1902 C. S. Slichter reduced this estimate to 3,000 to 3,500 feet.³³ In 1903 Chamberlin and Salisbury assign a depth of 800 to 1,600 feet over the surface above the

ground-water, according to the assumed average porosity of $2\frac{1}{2}$ per cent or 5 per cent at the surface and .0 per cent at a depth of 6 miles.³⁴ They estimate, however, that the average porosity is between 5 and 10 per cent for the outer lithosphere. C. R. Van Hise, in 1904, estimated it as equivalent to a layer over the continental land areas of 226 feet.³⁵ Finally, M. L. Fuller, after long experience with the subject in the water-supply work of the United States Geological Survey and on the basis of the best obtainable data, gave as his estimate 96 feet if the underground water were spread over the entire surface, and considered this amount as over rather than under the truth.^{35a}

Now, in the writer's contribution of 1901³¹ it was stated that, under extremely arid regions, the ground-water might fail entirely; that in deep mines, if impounded, it ceased at depths from 500 to 2,000 feet, below which pumping became unnecessary; but that cases such as the deep workings of the Comstock Lode, in regions of expiring igneous activity, must be ruled out, because the waters might be magmatic.

If, with Chamberlin and Salisbury, we assume porosities of 5 and 10 per cent, we have in the one case 25 to 50 feet of water; in the other, 100 to 200 feet. If we average all four of these estimates, by an odd coincidence we obtain 93.75 feet, checking remarkably with M. L. Fuller. This number would be reduced somewhat by the experience in arid regions, which have very deep ground-water level or none at all. If, again, we average the 500 feet and 2,000 feet of mining experience at 1,250 feet, and take Chamberlin and Salisbury's other assumptions of porosity at $2\frac{1}{2}$ per cent and 5 per cent, we obtain, respectively, 31.25 feet and 62.5 feet. Obviously, there is much less meteoric ground-water than was formerly believed to exist.

MAGMATIC EMISSIONS AS PRODUCERS OF VEINS

As the first decade of the present century passed into its second half, we find in 1906 Waldemar Lindgren's address at the Mexican International Congress on "The relation of ore deposition to physical conditions,"³⁶ wherein the agents which I have been passing in review are very much to the fore. In the same author's presidential address before the Geological Society of Washington, in December, 1907,³⁷ we observe quite as pronounced a tendency. At the close of 1907 J. E. Spurr's valuable contribution, entitled "A theory of ore deposition,"³⁸ published in this same month, there is a comprehensive and philosophical summary which I quote almost entire.

"This theory proposes that metalliferous fluids, from which most ore deposits are precipitated, are extreme differentiation phases of rock magmas;

that most ore-deposits and 'mineral veins,' as a class, represent one or the other of the extreme products of magmatic differentiation, and that the most striking chemical differences between ore-deposits is due (in the more important class representing the siliceous extreme) to successive precipitation in theoretically vertical zones, as the fluid migrates toward the surface, and with diminishing heat achieves more and more mature crystallization. Secondly, the differences between ore deposits in different regions depends upon the different metallographic magma-provinces."

For metallographic we now generally use metallogenetic. The author establishes earlier in the paper six zones of contrasted ores, depending on the remoteness of precipitation from the igneous source, a series which in whole or in part has been corroborated in many localities and by not a few observers, of whom I am one. The nearest to the igneous source are: 1, the pegmatites; 2, the free-gold auriferous pyrite zone with coarse quartz; 3, the cupriferous pyrite zone; 4, the galena-blende zone, often with silver; 5, rich silver and gold veins, with compounds of arsenic, antimony, bismuth, tellurium, and selenium, all "mobile" elements; 6, zone of barren earthy gangue minerals. The appreciation of magmatic emissions has cast no less light on the difficult problems of the mineral veins than on the obscure phenomena of the ancient metamorphic strata.

If you will recall my description above of the crystallizing of a magma in which mineralizers were dissolved, you will have before you the processes of gradual eviction. We now see that in their escape they take with them the minute amounts of the rarer metals dissolved in the mass and great quantities of silica and iron. Under circumstances of high temperature and high pressure, both favorable to effective solution, the mineralizers, or magmatic waters, may carry their dissolved burdens through the outer cooled shell, already cracked by shrinkage, and on through faults, bedding planes, and porous rocks of the inclosing walls. If intractable sandstones are met, quartzites are the chief result. If limestones or other limy sediments are encountered, contact zones, replacement ore-bodies, and bed-veins may be formed. In faults, fissure veins may be precipitated in any wall-rock. At the maximum of emission, vein formation goes relatively far. With waning heat, earlier, remoter zones may be repeated nearer the source.

WATER IN SOLID SOLUTION IN PITCHSTONES

Now, if an intrusive magma rich in dissolved water gas be suddenly chilled, as it sometimes is in a dike, and so quickly that no crystallization is set up, then we have pitchstones with from 5 to 10 per cent of water held in solid solution in the resulting glass. From pitchstones we get our

best idea of the amounts of water in an original deep-seated magma. The percentages are sufficiently high to convince us that the amount may be very great.

CONCLUSION

As a graduate student in the formative period, I was under the instruction and influence of one of the veterans and old-time heroes of American geological science, John Strong Newberry. All the predilections and all the teachings of my honored mentor were against the influence of igneous agents and, like those of a true modern Wernerian, were directed toward sedimentary processes and the waters which we have become accustomed to call meteoric in later years. Every predilection toward these views which could naturally be brought to bear militated against my own confidence in igneous forces in nature; but personal contact with the phenomena of the metamorphic rocks and the ancient crystallines, with dikes and intrusive masses, with veins and other ore deposits, inevitably presented problems whose solution it seemed impossible to find in any other way than in those outlined in this address. The same course of development has marked the growth and maturity of many geologists in the period covered by the life of our Society.

The Society was founded as the microscopic study of rocks became widespread and well established. This statement is tantamount to saying that its beginnings were coincident with intimate and accurate knowledge of the phenomena about which our predecessors more vaguely and generally reasoned. Our later years have been marked by such extended, detailed, and accurate mineralogical, chemical, and structural knowledge of rocks and their attendant phenomena as our forebears never possessed. We have learned our facts and evidence with painstaking care, and we are now interpreting them with confidence and with the conviction that we are at last on the way to the true solution of many hitherto puzzling phenomena. The intrusive rocks and their emissions constitute one of the outstanding groups of causes which, when applied to the ancient strata, to their recrystallization, their soaking with magmatic juice, their digestion and assimilation; when applied to the contact zones; when applied to the long series of veins from the pegmatites, which we also call dikes; to the quartz veins, which we have sometimes thought relatively cold-solution precipitates, and, lastly, which, when applied to the zonal distribution of our metals outwardly from an intrusive mass; in all these cases give us something intelligible, consistent, and illuminating.

For the future we may only hope that more light may be thrown on the puzzling problem of what great cause or causes periodically start the

batholiths upward; what brings them to rest where they differentiate; what starts their fractional parts on their renewed migrations toward the upper world, where they finally crystallize, solidify, and send their emissions outward. Is it isostatic readjustment? Is it slowing down of the earth's rotation and readjustment in shape? Is it the upsetting of equilibrium by some unusual combination of attractive forces from other bodies in outer space? Is it shrinkage from loss of heat? Is it a vast local breaking loose and escape of highly heated interior gases, the blow-pipe theory of R. E. Daly? Is it radioactivity in some little-understood manifestation, with local development of heat, or is it some *tertium quid*, as the old-time philosophers used to call it, not a third something or other, but a seventh something or other, which we have not yet thought of? Do all the common causes mentioned or any combination of them cover all our difficulties? Probably not; but some time in the future the *septimum quid* will be found.

REFERENCES

1. LARDNER VANUXEM: Geology of the Third District. New York State Survey, 1842, page 207.
 C. H. SMYTH, JR.: A third occurrence of peridotite in central New York. American Journal of Science, April, 1892, pages 322-327.
 Alnoite containing an uncommon variety of melilite. American Journal of Science, July, 1894, pages 54-65.
 Note on recently discovered dikes of alnoite at Manheim, New York. American Journal of Science, October, 1896, pages 290-292.
 Weathering of alnoite at Manheim. Bulletin of the Geological Society of America, volume 9, 1898, pages 257-268.
2. LARDNER VANUXEM: Geology of the Third District. New York State Survey, 1842, page 109.
 GEORGE H. WILLIAMS: On the serpentine (peridotite) occurring in the Onondaga salt group at Syracuse, New York. American Journal of Science, August, 1887, pages 137-145.
 Note on the eruptive origin of the Syracuse serpentine. Bulletin of the Geological Society of America, volume 1, 1890, pages 533-534.
 N. H. DARTON and J. F. KEMP: Newly discovered dike at Dewitt, near Syracuse, New York. American Journal of Science, June, 1895, pages 456-462.
 P. F. SCHNEIDER: New exposures of eruptive dikes in Syracuse, New York, with petrography by C. H. Smyth, Jr. American Journal of Science, July, 1902, pages 24-30.
3. LARDNER VANUXEM: Geology of the Third District. New York State Survey, 1842, page 169.

- J. F. KEMP: Peridotite dikes in the Portage sandstones near Ithaca, New York. *American Journal of Science*, November, 1891, pages 410-412.
- P. F. SCHNEIDER: Notes on some eruptive dikes near Ithaca, New York. *Proceedings of the Onondaga Academy of Sciences*, Syracuse, New York, volume 1, 1903, pages 130-136.
- V. H. BARNETT: Notice of the discovery of a new dike at Ithaca, New York. *American Journal of Science*, March, 1905, page 210.
4. J. F. KEMP and J. G. ROSS: A peridotite dike in the Coal Measures of southwestern Pennsylvania. *Annals of the New York Academy of Sciences*, volume 17, 1907, pages 509-518.
5. J. S. DILLER: Peridotites of Elliott County, Kentucky (eastern Kentucky). *Bulletin of the United States Geological Survey*, number 38, 1887.
Mica-peridotite from Kentucky (Crittenden County, western Kentucky). *American Journal of Science*, October, 1892, pages 286-289.
6. J. C. BRANNER and R. N. BRACKETT: Peridotite of Pike County, Arkansas. *American Journal of Science*, July, 1889, pages 50-59.
J. FRANCIS WILLIAMS: Igneous rocks of Arkansas, volume 2 of Arkansas Geological Survey, Annual Report for 1890, pages 378-391. In connection with possible diamond mining, many recent short papers have been issued.
7. EZEQUIEL ORDONEZ: Ejemplos probables de Tubos de Erupcion. *Memorias de la Sociedad Alzate*, volume 22, 1904-05, pages 141-150.
The later literature of the Tampico oil field has many additional references.
8. W. H. BUCHER: Cryptovolcanic structure in Ohio of the type of the Steinheim Basin (abstract). *Bulletin of the Geological Society of America*, volume 32, 1921, page 74.
9. H. S. WASHINGTON: Professional Papers numbers 14 (1903), 28 (1904), and 99 (1917), United States Geological Survey. Numbers 14 and 99 contain critical discussions of analyses.
10. R. T. CHAMBERLIN: The gases in rocks. Carnegie Institution, Washington, 1908.
11. W. C. BRÖGGER: Die Mineralien der Syenitpegmatitgänge der südnorwegischen Augit-und Nephelin-syenite. *Zeitschrift für Krystallographie*, volume 16, 1890.
12. JOSEPH BARRELL: Relations of subjacent igneous invasion to regional metamorphism. *American Journal of Science*, January, 1921, pages 1-19; February, pages 174-186; March, pages 255-267, especially page 261.
13. J. F. KEMP: Gabbros on the western shore of Lake Champlain. *Bulletin of the Geological Society of America*, volume 5, 1894, pages 213-224, especially pages 218-221.

14. The reaction rims of the last citation and various others are discussed at length by J. J. Sederholm in "On synantetic minerals and related phenomena" (reaction rims, corona minerals, kelyphite, myrmekite, etcetera). Bulletin de la Commission, géologique de Finlande, number 48, 1916.
15. J. J. SEDERHOLM: Bulletin last cited, page 142.
16. J. F. KEMP: An orbicular granite from Quonochontogue Beach, Rhode Island. Transactions of the New York Academy of Sciences, volume 13, 1894, pages 140-144.
17. ———: A new spheroidal granite. Science, volume 18, 1903, pages 503-504.
18. ———: Granites of southern Rhode Island and Connecticut, etcetera. Bulletin of the Geological Society of America, volume 10, 1899, pages 361-382, especially page 371.
19. A. L. DAY and E. S. SHEPHERD: Water and volcanic activity. Bulletin of the Geological Society of America, volume 24, 1913, pages 573-606.
20. C. N. FENNER: The Katmai region of Alaska and the great eruption of 1912. Journal of Geology, volume 28, 1920, pages 569-606.
21. F. C. LINCOLN: Magmatic emanations. Economic Geology, volume 2, 1907, pages 258-274.
22. F. D. ADAMS and A. E. BARLOW: Geology of the Haliburton and Bancroft areas, Province of Ontario. Canada Geological Survey, Memoir 6, 1910, pages 101-112, especially page 106.
- 22a. J. E. WOLFF: The Franklin Furnace, New Jersey, Folio. Number 161, United States Geological Survey, 1908.
- 22b. C. N. FENNER: On the mode of formation of certain gneisses in the highlands of New Jersey. Journal of Geology, volume 22, 1914, pages 594-612, 694-702.
- 22c. JOSEPH BARRELL: Physical effects of contact metamorphism. American Journal of Science, April, 1902, pages 279-296.
23. W. LINDGREN: Copper deposits of the Clifton, Morenci District. Professional Paper number 43, United States Geological Survey, 1905, pages 134, 154-165.
24. J. F. KEMP: The copper deposits of San José, Tamaulipas, Mexico. Bulletin number 4, 1905, American Institute of Mining Engineers, pages 885-912. Transactions, volume 36, 1906, pages 178-203.
25. J. H. VOGT: Haloid emissions favored in "Om dannelse af Jernmalmforekomster," pages 62-63. Résumé in deutscher Sprache, page 147. Norwegian Geological Survey, Kristiania, 1892.

BEYSCHLAG, KRUSCH, and VOGT: Die Lagerstätten, etcetera, volume I, 1910, page 349.

English translation by S. J. Truscott, volume 1, 1914, page 352.

26. C. K. LEITH and E. C. HARDER: Iron ores of the Iron Springs District, southern Utah. Bulletin of the United States Geological Survey, number 338, 1908, page 77.

27. V. M. GOLDSCHMIDT: Die Kontaktmetamorphose in Kristianiagebiet, 1911, page 269, for specularite; page 250, for zincblende.

28. J. F. KEMP: On the formation of garnet zones at the contacts of eruptive rocks and limestones. Mining and Scientific Press, March 24, 1906.

"Contact deposits," in the volume "Types of Ore Deposits," pages 190-201. San Francisco, 1911.

Notes on garnet zones on the contact of intrusive rocks and limestones. Journal of the Canada Mining Institute, volume 15, 1912, pages 171-186. Twenty-six analyses of garnets from contact zones and eleven cases of the succession of minerals are given.

29. C. A. STEWART: The geology and ore deposits of the Silverbell Mining District, Arizona. Transactions of the American Institute of Mining Engineers, volume 43, 1912, pages 240-290, especially pages 272-279.

29a. See final reference under number 28.

30. J. H. L. VOGT: A series of papers in volume I of the Zeitschrift für praktische Geologie, 1893.

31. J. F. KEMP: The rôle of the igneous rocks in the formation of veins. Transactions of the American Institute of Mining Engineers, volume 31, 1901, pages 169-198, especially pages 184-195; compare, also, volume 33, 1902, pages 699-714.

32. ACHILLE DELESSE: Bulletin de la Société Géologique, France, second section, volume 19, 1861-62, page 64, as cited by Chamberlin and Salisbury. See 38, below.

33. C. S. SLICHTER: Motions of underground waters. Water-supply and Irrigation Papers, United States Geological Survey, number 67, 1902, page 14.

34. CHAMBERLIN and SALISBURY: Geology, volume I, 1903, pages 209-210; page 221 of second edition, 1909.

35. C. R. VAN HISE: Treatise on metamorphism. United States Geological Survey, Monograph, number 47, 1904, pages 128-129, 570-571.

- 35a. M. L. FULLER: Amount of free water in the earth's crust. Water-supply and Irrigation Papers, United States Geological Survey, number 160, pages 59-60 and 72.

36. W. LINDGREN: The relation of ore deposition to physical conditions. Tenth International Geological Congress, Mexico, 1906. *Compte Rendu*, volume 2, 1907, pages 701-721. *Economic Geology*, volume 2, 1907, pages 105-127.
37. ———: Present tendencies in the study of ore deposits. *Economic Geology*, volume 2, 1907, pages 743-762.
38. J. E. SPURR: A theory of ore deposition. *Economic Geology*, volume 2, 1907, pages 781-795, especially pages 791 and 795.

SOME PROBLEMS CONNECTED WITH THE DAKOTA
SANDSTONE¹

PRESIDENTIAL ADDRESS BY TIMOTHY W. STANTON

(Read before the Paleontological Society December 29, 1921)

CONTENTS

	Page
Introduction.....	255
Location, character, and fauna of the sections.....	255
The typical exposures.....	255
Nebraska sections.....	257
Kansas sections.....	257
Texas section.....	261
Relationships of the fauna.....	262
General discussion of the origin of the sections.....	263
Wyoming and Colorado sections.....	265
New Mexico sections.....	269
Review and conclusion.....	270

INTRODUCTION

There are still problems connected with the Dakota sandstone, though that formation was named and described 60 years ago and has been under investigation by many geologists at frequent intervals ever since. Even such simple questions as its stratigraphic limits and its areal extent have not received answers of sufficient clearness to be generally accepted, and its mode of origin is still a subject of discussion.

LOCATION, CHARACTER, AND FAUNA OF THE SECTIONS

THE TYPICAL EXPOSURES

The typical exposures from which the formation took its name are in the bluffs bordering the Missouri River valley "back of the town of Dakota," a village in northeastern Nebraska about 6 miles south of Sioux City, Iowa, but the outcrops which were early studied and from which

¹Manuscript received by the Secretary of the Society February 20, 1922.

Published by permission of the Director of the U. S. Geological Survey.

the first collections of both plants and mollusks were obtained are distributed along both banks of the Missouri from Ponca, Nebraska, to Tekamah, Nebraska, a distance of about 60 miles. The total thickness of exposed rocks referable to the Dakota in the neighborhood of Sioux City, from the mouth of Big Sioux River to Sargents Bluff, is about 100 feet, and if the section be extended down to Tekamah, so as to include the plant-bearing beds at that place, at Decatur, and at Blackbird Hill, it will still probably cover less than the upper 200 feet of the Dakota sandstone. The invertebrates described from the mouth of Big Sioux River must have come from the upper 50 feet of the formation and probably from the uppermost sandstone bed. The following are figured by Meek:²

- Trigonarca siouxensis* (Hall and Meek).
- Margaritana nebrascensis* Meek.
- Arcopagella? macrodonta* Meek.
- Cyrena dakotensis* Meek and Hayden.
- Pharella dakotensis* Meek and Hayden.
- Mastra siouxensis* Meek and Hayden.
- Cast of the burrow of some unknown mollusk.

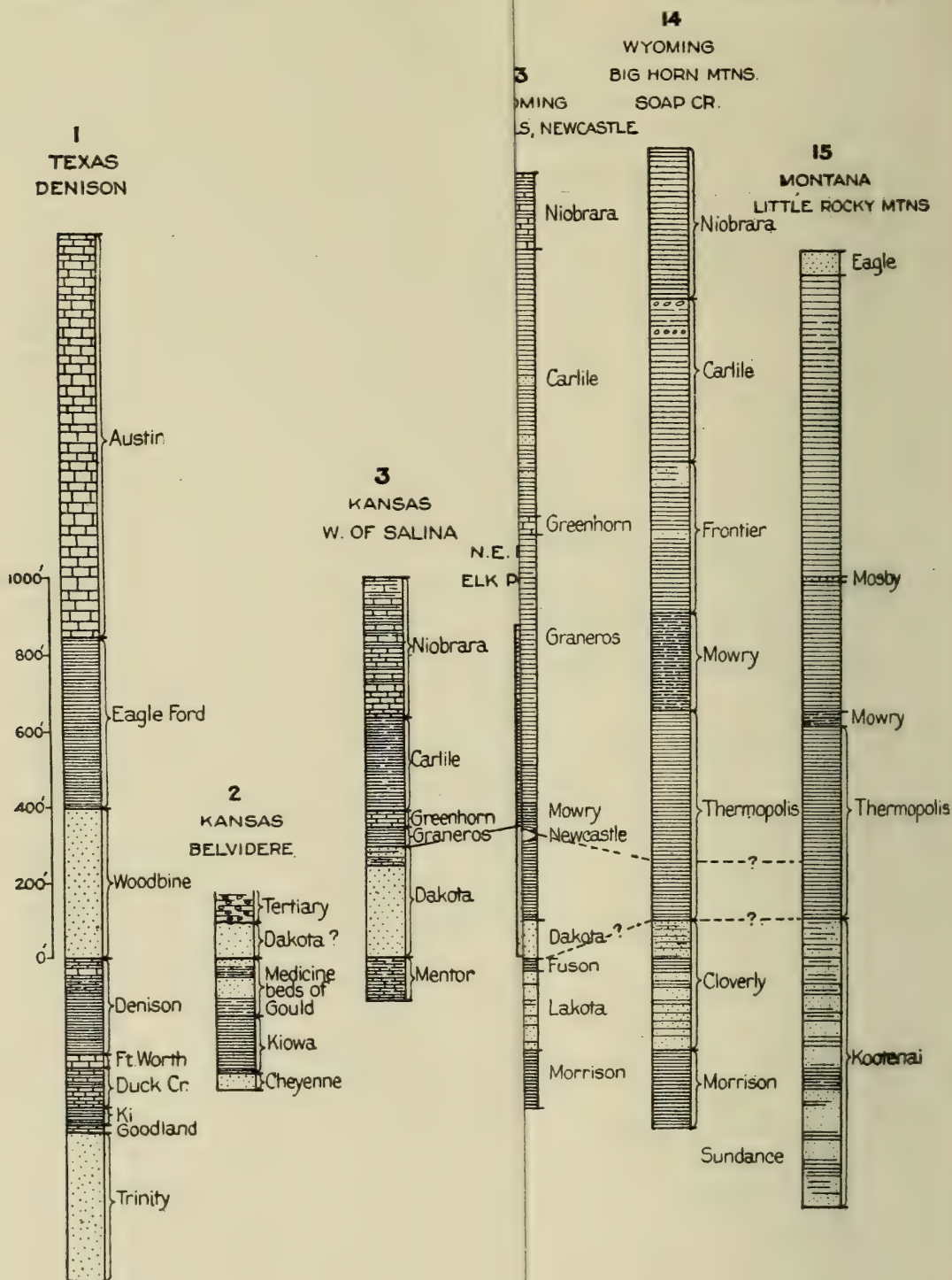
Another fossiliferous locality in the same neighborhood, discovered by C. N. Gould³ near Jackson, Nebraska, and collected from by myself in 1920, is in the upper 10 feet of the Dakota and has yielded the following forms:

- Ostrea* sp.
- Trigonarca siouxensis* (Hall and Meek).
- Arcopagella? macrodonta* Meek?
- Pharella?* sp.
- Corbula hicksii* White.
- Martesia?* sp. casts of burrows in wood.
- Pseudomelania?* sp.
- Vivipara hicksi* White?
- Volutoderma?* sp.
- Vertebra of fish.
- Vertebra of turtle.
- Tooth of crocodile.

Most of the invertebrates of these two lists are marine, but an admixture of fresh and brackish water forms is indicated by the species referred to *Margaritana*, *Pharella*, *Cyrena*, and *Vivipara*. The sediments also indicate a struggle between sea and land along a low sandy shore with swamps, lagoons, and inlets. There are rapid changes from sand to shale,

² U. S. Geol. Survey of the Territories, vol. 9, pl. i, 1876.

³ Kansas Acad. Sci. Trans., vol. 17, 1901, p. 168.



both vertically and laterally, so that the details of near-by sections always vary. There are local thin beds of lignite, the most persistent of which is near the top. The bedding is everywhere irregular, and the alternations of shale and sandstone toward the top form such a gradual transition to the overlying Graneros (lower Benton) shale that in most sections the line between Dakota and Graneros is more or less arbitrary. Finally, however, the sea prevailed and the purely marine Graneros shale was deposited over the whole region to a depth of 70 to 100 feet, followed by the chalky beds of the Greenhorn limestone full of *Inoceramus labiatus* and foraminifera, of which the most abundant form is *Globigerina*. A few miles to the west a higher shale, the Carlile, is seen, overlain by the chalky limestone and shale of the Niobrara. The section is represented by number 4 of the chart (plate 4).

The lower part of this section below the upper hundred feet of the Dakota is based on well data, which indicate that rocks of Dakota type have a total thickness of 350 or 400 feet, and no evidence has been found that would suggest the reference of any of these rocks to an older formation.

NEBRASKA SECTIONS

On Platte River 5 miles southeast of Ashland, Nebraska, and about 100 miles south of the typical exposures of the Dakota which have just been discussed, a basal Cretaceous sandstone is exposed resting unconformably on Pennsylvanian limestone. No fossils have been found in it, but there seems to be no good reason for questioning its reference to the Dakota.

The upper part of the Dakota near Fairbury, southern Nebraska, has yielded a faunule of fresh and brackish water mollusks described by C. A. White⁴ under the following names:

Unio barbouri.

Unio sp.

Corbula hicksii.

Goniobasis jeffersonensis.

Goniobasis sp.

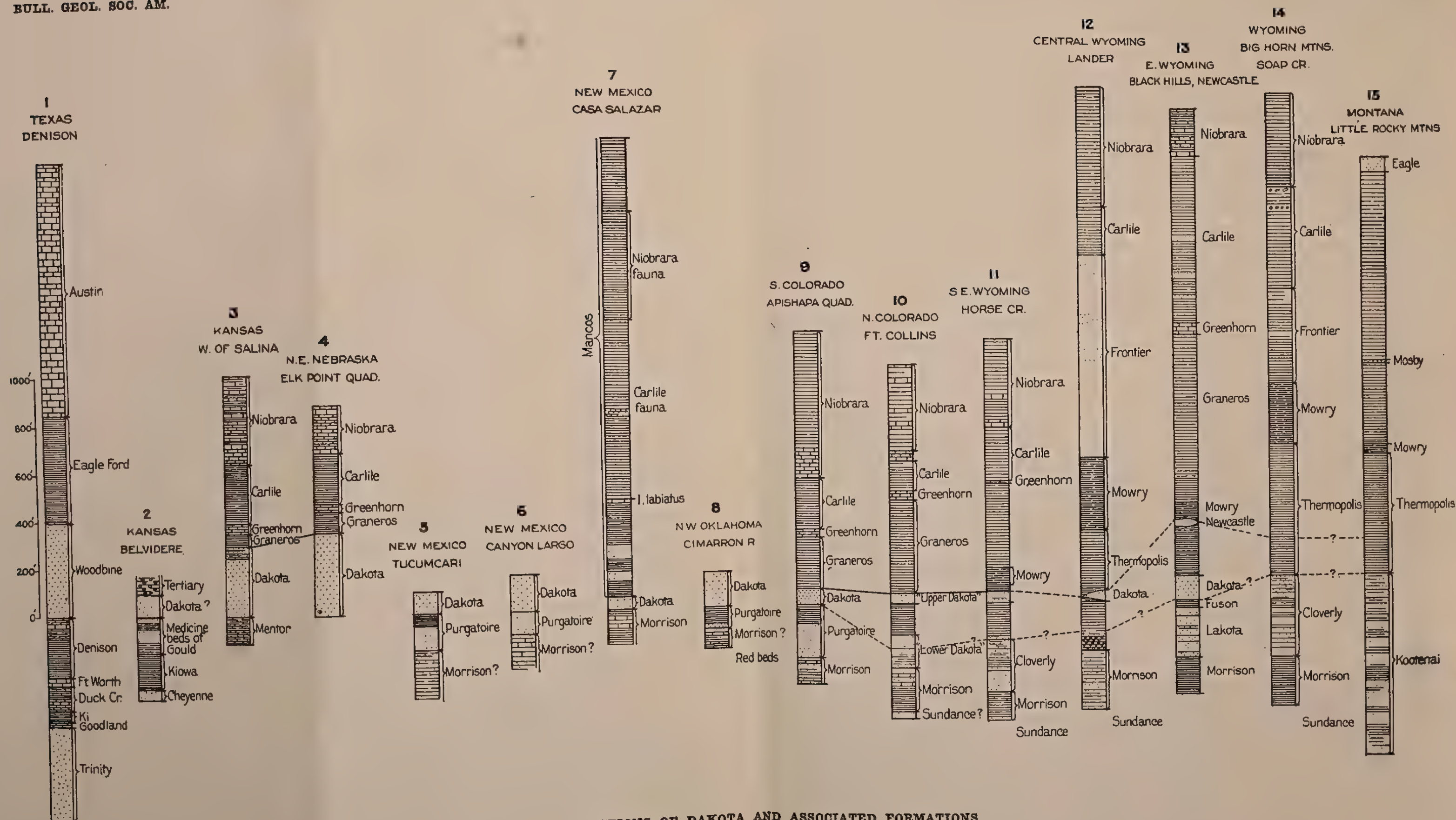
Viviparus hicksii.

Pyrgulifera meekii.

KANSAS SECTIONS

Farther south in northern and central Kansas the top of the Dakota shows the same close relationship as in eastern Nebraska with the over-

⁴ U. S. Nat. Mus. Proc., vol. 17, 1894, pp. 131-138.



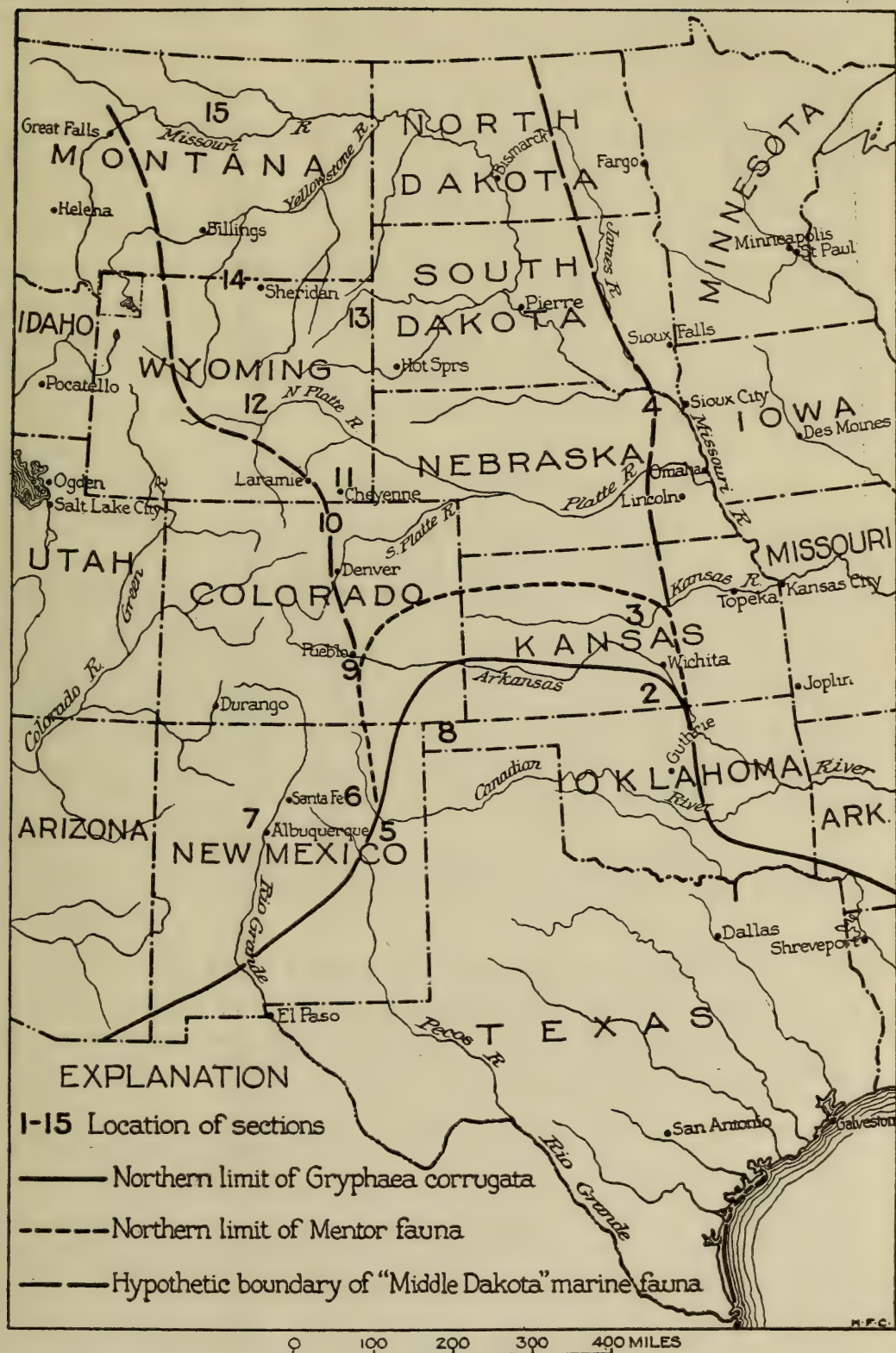
COLUMNAR SECTIONS OF DAKOTA AND ASSOCIATED FORMATIONS

lying marine shale of Graneros age, and the limestones filled with *Inoceramus labiatus* are less than 100 feet above the top of the Dakota. The upper 100 feet or so of the Dakota here are, beyond reasonable doubt, the equivalent of the typical Dakota exposures in the neighborhood of Sioux City. Stratigraphy, lithology, fossil plants, and invertebrates all support this correlation, and no one from the study of these rocks alone would think of putting them in a different system or series from the overlying marine shale. But in central Kansas, in the neighborhood of Salina and southwestward, the Cretaceous rocks are well exposed from the top of the Dakota, and higher, down to the contact of the Cretaceous with the Permian, and in the lower hundred feet of these Cretaceous exposures there is a marine fauna which is now known to be closely related to the Comanche fauna of Texas. In the early days, when the existence of the Comanche series was unknown, these beds, with their marine fauna, were unhesitatingly referred to the Dakota. Later, as the stratigraphy and geologic history of the general region became better known, the base of the Dakota in this area and the relation which that formation holds with the Comanche series became important questions. After the field season of 1898, when, in company with Lester F. Ward and C. N. Gould, I had studied the Cretaceous of southern and central Kansas, I announced⁵ that our "field-work in Kansas shows a very close stratigraphic connection between the Dakota leaf-bearing sandstone and the underlying marine beds of the Comanche series," a conclusion which no one has seriously questioned since. I believed then, however, and I still believe, that the fauna with a strong and definite Comanche element in central Kansas is confined to the lower, or Mentor, beds, above which there are 200 to 300 feet of Dakota rocks. It is these rocks above the Mentor which have yielded probably 90 per cent or more of the described Dakota flora. The localities known as Fort Harker, Fort Ellsworth, Ellsworth County, and Delphos are all in this part of the section, and it is reasonably certain that nearly all of the Dakota plants credited to Kansas without more definite locality were collected by Sternberg, West, and others from the same horizons, ranging through, perhaps, 100 feet of strata near the localities mentioned.

Logan's⁶ description of the Dakota of central Kansas was perplexing because he divided the Dakota formation into a lower, or ferruginous, division containing all the Dakota flora and no mollusks, and an upper, or saliferous, shale division in which the fossils are all marine inverte-

⁵ Twentieth Ann. Rept. U. S. Geol. Survey, pt. 1, p. 64.

⁶ W. N. Logan: The Upper Cretaceous of Kansas. University Geological Survey of Kansas, vol. 2, 1897, pp. 195-234. The Dakota is described on pages 206-215.



MAP SHOWING LOCATION OF SECTIONS AND DISTRIBUTION OF WASHITA AND "MIDDLE DAKOTA" FAUNAS

brates consisting largely of Comanche species, with a few from the typical Dakota fauna. Logan's stratigraphy and paleontology of the upper part of the Dakota was adopted by Twenhofel⁷ and apparently forms the chief basis for his conclusion that the Dakota is Comanchean. Logan's failure to mention any localities at which his fossils were collected made it impossible to check his results in the field, and I therefore wrote him under date of October 11, 1905, inquiring about the localities from which he obtained the "upper Dakota" fossils listed in his report, saying that "the matter is of immediate interest to me now, in connection with recent field-work, and I write to ask whether, after so many years, you can give me exact localities and horizons for the Dakota invertebrates you have listed; also, whether the collections are still at Lawrence, assembled by horizons and localities, and to whom I should apply to borrow them for brief examination."

Professor Logan's reply of October 18, 1905, is in part as follows:

"You will doubtless recognize the strong 'Mentor' phase of that list of fossils. At that time I included the Mentor beds in the Dakota. Had I seen Professor Prosser's paper⁸ that list would not have been given as belonging to the Dakota. That I thought this horizon identical with the upper Dakota will be seen from a statement to Prosser on page 189 of the same report. However, those fossils spoken of as being similar to the Mentor fossils have never been determined, to my knowledge. I think I sent them all to Prosser. . . . The localities are: at Beloit, Mitchell County, just below the mill on Solomon River, and at Denmark, Lincoln County, from rock taken from the lignite mines at that place. The shells are abundant at this place. At Beloit they occur in sandstone and are not abundant.

"I have no doubt that some of my determinations of the Mentor fossils were incorrect, but you will see by comparing with your own list on page 185 that some are right."

It is evident from this statement that the larger part, if not all, of the fossil mollusks listed by Professor Logan as from the upper beds of the Dakota really came from the Mentor horizon, probably in the area around Marquette, where at that time he had erroneously assigned some of the

⁷ W. H. Twenhofel: The Comanchean and Dakota strata of Kansas. Am. Jour. Sci., 4th ser., vol. 49, 1920, pp. 281-297. See especially pages 286, 287.

⁸ Charles S. Prosser: The Upper Permian and the Lower Cretaceous. University Geological Survey of Kansas, vol. 2, pp. 51-194. The statement on page 189 referred to in Professor Logan's letter is included in the following quotation: "Mr. W. N. Logan has also sent me Mentor fossils from the 'Natural corral' in McPherson County supposed to be the same locality studied by Mr. Beede, among which are specimens of *Trigonia emoryi* Con. Mr. Logan wrote me that he 'had found fossils in the upper and middle horizons of the Dakota which seem to be identical with the Mentor fossils.' From a sandstone at the extreme upper limit of the Dakota near Beloit Mr. Logan has also collected lamellibranch shells that have not been identified specifically and may possibly belong in a different fauna from that of the Mentor."

conspicuous sandstones to a position near the top of the Dakota. For convenience of reference his lists may be repeated here, as follows:

From thin sandstone layers of first shale bed:

- Corbicula subtrigonalis* Meek.
- Trigonarca salinaensis* Meek.
- Yoldia microdonta* Meek.
- Crassatellina oblonga* Meek.
- **Arcopagella macrodonta* Meek.
- Tellina subscitula* Meek.
- Protocardia salinaensis* Meek.
- Cardium kansasense* Meek.
- **Cyrena dakotensis* (Meek and Hayden).
- **Margaritana nebrascensis* Meek.
- **Mastra siouxensis* Meek and Hayden.
- **Tellina modesta* Meek.

From fossil bed in saliferous shale:

- Leptosolen conradi* Meek.
- **Pharella dakotensis* Meek and Hayden.
- Cardium kansasense* Meek.

In 1906 the localities near Beloit and Denmark, Kansas, were visited by me for the purpose of studying the marine horizon discovered by Logan at the top of the Dakota. At Beloit the following forms were collected:

- Ostrea* sp. Large simple form.
- Anomia* sp.
- Modiolus* sp. Related to *M. filisculptus* Cragin.
- Gervillia* sp.
- Trigonarca siouxensis* Hall and Meek.
- Cyrena?* sp. Resembles *C. dakotensis* Meek.
- Tellina* sp.
- Corbula hicksii* White.
- Corbula* sp.
- Anatina* sp.
- Pseudomelania?* sp.
- Anchura* sp.

Approximately the same horizon in the coal mine shafts two miles north of Denmark, Kansas, yielded the following:

- Ostrea* sp. Small simple form.
- Anomia* sp.
- Modiolus* sp. Related to *M. filisculptus* Cragin.
- Arca* sp.
- Anatina* sp. Same as at Beloit.

* These species are not known in the Mentor fauna and are probably incorrectly identified.

These fossils show no closer relationship with the Mentor and other upper Comanche faunas than is indicated by the presence of some genera in common. The specific identities all connect it with the upper Dakota fauna of Nebraska.

The Cretaceous section of central Kansas, as summarized in number 3 of the chart, includes the chalky limestone of the Niobrara, a shale representing the Carlile, limestones of the *Inoceramus labiatus* zone representing the Greenhorn, a shale less than 100 feet thick representing the Graneros, the plant-bearing, largely continental sandstones of the Dakota with a marine bed in the extreme upper part, and about 100 feet of sandstones and shales which are largely marine, though they include some shore and lagoon deposits with plants of Dakota aspect. The fauna of this basal, or Mentor, part of the Cretaceous section includes enough characteristic Comanche species that also occur in the Kiowa shale of southern Kansas and in the Denison formation of northern Texas to justify its correlation with the upper part of the Washita group, though the absence of *Gryphæa corrugata*, *G. navia*, and many others of the most abundant and characteristic species of the Kiowa and of the Denison is noteworthy. The Mentor fauna does not recur above the basal 100 feet of the section.

In the southern Kansas section, represented by number 2 of the chart, the upper part of the Dakota and all of the later Cretaceous formations have been removed by erosion; there is a greater thickness of marine beds, with a well developed and distinctive Comanche fauna, represented in the Kiowa shale and the overlying variable shales and sandstones which seem to form a transition to the Dakota; and at the base is the Cheyenne sandstone, about 50 feet thick, which Twenhofel has interpreted as of terrestrial origin, deposited on relatively flat lands near the sea. The flora of the Cheyenne sandstone resembles the Dakota flora, but may be specifically distinct. The Kiowa fauna is characterized by the abundance of *Gryphæa corrugata*, *G. navia*, and many other Washita forms, together with a few species, such as *Exogyra texana* and *Schlenbachia acutocarinata*, which in Texas are either restricted to or more abundant in the underlying Fredericksburg group.

TEXAS SECTION

In northern Texas, near Denison, the section represented by number 1 of the chart shows a much greater thickening of marine sediments in the Washita group, beneath which are thin representatives of the Fredericksburg and Trinity groups of the Comanche series. Beginning at the bottom of the Washita, the succession is Kiamichi clay, Duck Creek forma-

tion, Fort Worth limestone, and Denison formation. The time equivalents of all of these formations are probably represented in the Cheyenne sandstone and Kiowa shale of southern Kansas, but in the Mentor of central Kansas apparently only the Denison formation, and possibly only its upper part, is represented. Above the Denison formation lies the Woodbine sand, which is considered the approximate equivalent of the Dakota, the Eagle Ford clay, which represents the Benton sequence of the north interior region, and the Austin chalk, which is correlated with the Niobrara.

The Woodbine sand in its upper part contains a considerable marine fauna which has not yet been fully described. Cragin⁹ lists the following species:

- Ostrea soleniscus* Meek.
- Ostrea carica* Cragin.
- Exogyra ferox* Cragin.
- Exogyra columbella* Meek.
- Pteria salinensis* White.
- Aguileria cumminsi* White.
- Modiolus filisculptus* Cragin.
- Arca galliennae* var. *tramitensis* Cragin.
- Trigonarca siouxensis* Meek and Hayden.
- Cytherea leveretti* Cragin.
- Turritella coalvillensis* Meek.
- Turritella renauxiana* d'Orbigny.
- Cerithium tramitensis* Cragin.
- Cerithium interlineatum* Cragin.
- Neritopsis tramitensis* Cragin.

RELATIONSHIPS OF THE FAUNA

There are a number of undescribed species in this fauna, including two or more species of *Acanthoceras* in the collections of the United States Geological Survey. The relationships which this fauna suggest to me are on the one hand with the Dakota fauna of eastern Nebraska and north central Kansas and on the other with the lowest Mancos fauna of central New Mexico and southern Utah. The geologists of the Texas Bureau of Economic Geology and Technology have assigned the Woodbine sand to the Washita group and tentatively correlated it with the Buda limestone of central and southern Texas, but the evidence on which this classification and correlation were based has not been published. There is certainly no direct paleontologic evidence that would justify the correlation.

⁹ F. W. Cragin: Contributions to the invertebrate paleontology of Texas. Geological Survey of Texas, 4th Ann. Rept., 1893.

GENERAL DISCUSSION OF THE ORIGIN OF THE SECTIONS

The sections so far considered are all near the eastern margin of the great sea which in later Cretaceous time covered the Great Plains and a large part of the Rocky Mountains. During a large part of Comanche time the northern shore of the Mexican sea was in northern Texas, or not far beyond it, as evidenced by the nature of the Trinity and Paluxy sands and the northward thinning of all the limestones. In later Comanche time, however, about the beginning of the Washita, a somewhat rapid northward transgression of the sea began, which soon reached southern Kansas and by the close of the Washita had extended as far north as Salina, in central Kansas. The advance was probably of a halting nature, with possibly slight reversals of movement, so that with shallow waters, low-lying lands, shifting currents, and varying amounts of sediment received, the shoreline sometimes rapidly shifted many miles both north and south and east and west, thus giving alternations of purely marine beds with those that represent swamp or terrestrial conditions. So far as can be determined from the rocks now exposed along the eastern shore, the sea did not reach northeastern Nebraska until after the close of Washita and Comanche time.

How far north the Comanche sea extended in the western plains and Rocky Mountains is one of the questions that need more evidence than is now available before a satisfactory answer can be given, but the few data that have accumulated may be considered. The evidence must be sought toward the western margin of the Great Plains. The nearest exposures west of the typical Dakota area of eastern Nebraska are around the margin of the Black Hills uplift. The details of the section vary from place to place, but I have taken as representative of the general conditions the section in the Newcastle quadrangle on the west side of the Black Hills (number 13 of the chart). The diagram represents the section from the Niobrara down to the marine Jurassic Sundance. The Dakota as now generally interpreted is the upper sandstone of the "hogback" which surrounds the Hills, and between it and the Sundance are the Fuson shale, Lakota sandstone, and Morrison shale. The Fuson and the Lakota are both plant-bearing, and the evidence of the plants apparently shows that both these formations are older than the Washita, their floras being more primitive than that of the Cheyenne and comparable with the Potomac floras of Maryland and Virginia. This fact should be kept in mind in considering the relations of the Purgatoire formation with the Morrison in southern Colorado and in interpreting the meaning of the dicotyled-

onous flora which Lee¹⁰ and Knowlton¹¹ have reported from "the type section of the Morrison formation." The plants from Morrison, Colorado, are obviously not only younger than the Morrison formation, but also younger than the Lakota and Fuson.

The Black Hills section above the Dakota, as compared with the eastern Nebraska section, shows a thickening of all the marine Cretaceous formations with the possible exception of the Niobrara. The Niobrara and the Greenhorn, with their characteristic faunas, serve as convenient key horizons for the accurate correlation of the different parts of the section, and between these formations the zone of *Prionocyclus wyomingensis* and *Scaphites warreni* is another key horizon with a characteristic fauna which is very widely distributed in the Rocky Mountain region. Still another key horizon beneath the Greenhorn limestone is the Mowry shale, which is useful in some areas to the west where the Greenhorn is not recognizable.

Just beneath the Mowry member, and separated from it by a few feet of dark shale, is a variable sandstone, ranging from 0 to 30 or 40 feet in thickness, which is worthy of more than passing mention. Darton treated it as a member of the Graneros shale, lying about 200 feet above its base. More recently Hancock named it the Newcastle sandstone member, saying that it is the "muddy" sand of the drillers in that area. Darton reported that a lenticular sandstone 15 feet thick in the same stratigraphic position on the east side of the Black Hills, near Hermosa, South Dakota, contains abundant fossil plants, and in July, 1921, I visited the locality 2 miles northwest of Hermosa and made a collection which has been examined by F. H. Knowlton, who reported on them as follows:

"This material is very fragmentary, most of the leaves being without margins and few with complete nervation. The appearance of the matrix and the general facies of the leaves suggest Dakota, and without information to the contrary they would probably have been so determined. For instance, I note what appears to be:

Salix proteaefolia Lesq.?

Laurus antecedens Lesq.?

Andromeda parlatorii Heer?

"All are Dakota species."

Does this thin sandstone really belong to the Dakota? If so, should the Dakota also include the upper sandstone of the main hogback as well as the 200 feet of shale between these sandstones? These questions are

¹⁰ Am. Jour. Sci., 4th ser., vol. 49, pp. 183-184.

¹¹ Idem, pp. 189-194.

pertinent in connection with other sections in Wyoming and Colorado soon to be considered. The dark shale between the sandstones is apparently of marine origin, but no fossils have been reported from it in the Black Hills region.

Continuing the comparison of sections to the northwest, the next section diagrammatically summarized on the chart (number 14) is the Soap Creek section, in southern Montana, at the east base of the Bighorn Mountains. It was described by W. T. Thom, Jr., and G. F. Moulton in a recent press bulletin of the United States Geological Survey. The principal key horizons for our comparison are the Niobrara and the Mowry. The Dakota, as such, is not recognizable. Is it represented in the 550 feet of Thermopolis shale beneath the Mowry or is it in the top of the Cloverly, which when originally described was supposed to include the equivalent of the Dakota?

Near the Little Rocky Mountains in northeastern Montana the section recently studied by A. J. Collier (number 15 of chart) is similar to the Soap Creek section, in that the Dakota is not recognizable and the interval between the Mowry shale and the varicolored continental deposits here called Kootenai is occupied by 500 feet of dark shale corresponding to the Thermopolis.

The recognition of the Dakota sandstone, as such, at any localities farther west and north is not believed to be justified.

WYOMING AND COLORADO SECTIONS

Turning southward again, let us review several representative sections east of the Rocky Mountain front in Wyoming and Colorado. The first one in central Wyoming (number 12 of the chart), between Lander and Casper, is generalized from the descriptions of Woodruff¹² and Hares.¹³ Here the Niobrara is recognizable by its fauna, and the Mowry is conspicuous as a lithologic and topographic feature. Beneath the Mowry, and separated from it by 150 to 300 feet of Thermopolis shale, is a sandstone, varying in thickness from 0 to 60 feet, which has yielded a characteristic Dakota flora, as determined by Knowlton, and the sandstone was therefore identified as the Dakota. Beneath it there are dark shales, with some thin sandstones, having a thickness of 100 to 350 feet and resting on a conglomerate of varying thickness up to 60 feet, which in turn overlies the Morrison. In the dark shale beneath the Dakota of this section I found some marine pelecypods, and stated, as quoted in Woodruff's report, that "from its stratigraphic position and its general char-

¹² U. S. Geol. Survey, Bull. 452, 1911, pp. 16-22.

¹³ U. S. Geol. Survey, Bull. 641, 1917, pl. 23.

acteristics, this faunule ought to be Lower Cretaceous, but I have not been able to make specific identifications of any forms characteristic of the Lower Cretaceous or the Comanche series." In fact, no genera were identified; but, on account of the recognition of a marine deposit beneath the Dakota and distinct from the Morrison, it was classified tentatively as Lower Cretaceous. In beds of this same unit near Lander, Wyoming, Williston¹⁴ has recorded the occurrence of crocodile and shark teeth, among which he identified four species "with species obtained from the Mentor beds of the Lower Cretaceous of Kansas." Williston believed that the bed containing the fish teeth, together with the underlying sandstone and conglomerate, belonged in the Morrison formation, which he was discussing under the term "Atlantosaurus beds." Most of the Kansas fish teeth with which comparisons were made came from the "Greenleaf sandstone," which was described as overlying the Kiowa shale, but some came from the unquestioned Kiowa. *Scylliorhinus*, the only genus mentioned in Williston's paper, is recorded from the "Greenleaf sandstone" only. Species based on teeth of sharks and crocodiles, as usually identified, have a considerable stratigraphic range.

Attention is called to the possibility or even the probability that the Dakota sandstone of this section is the same as the Newcastle sandstone of the Black Hills section, and that the underlying shale and possibly some lower beds are also of Dakota age.

A section in southeastern Wyoming, on Horse Creek, north of Cheyenne (number 11 of the chart), is almost equidistant from the Lander area and the Black Hills. The diagram is somewhat generalized from my own field-notes, from the section published by Darton in the Laramie-Sherman folio, and from a section measured by W. T. Lee which he has kindly permitted me to use. In this section, a short distance beneath the Mowry shale, there is a sandstone 25 to 50 feet thick, comparable in character and position with the Newcastle sandstone of the Black Hills section and, like it, treated by Darton as a member in the Graneros shale. Beneath the sandstone there are dark shales and thin-bedded sandstones with a thickness of 150 feet which contain fish bones and scales and marine invertebrates identified as

Pteria sp., related to *P. gastrodes* Meek.

Inoceramus sp., related to *I. labiatus* Schlotheim.

Turritella? sp.

The comparisons are with species of the Colorado group, but they might as well have been with *Pteria salinaensis* White and *Inoceramus coman-*

¹⁴ Journal of Geology, vol. 13, 1905, pp. 347, 348.

cheanus Cragin, both of which are Washita species. Between this marine shale and the Morrison are the rocks which Darton mapped as Cloverly, including a conglomerate identical in character with the conglomerate above the Morrison in the Lander section. Again the question must be raised, What is Dakota in this section? Is it the sandstone next below the Mowry? Is it this sandstone plus the underlying shale, plus, perhaps, a part of the lower sandstones? Or is it entirely represented in the rocks which Darton here called Cloverly? The fossils do not give a decisive answer. They are of types represented by similar forms both in the Comanche and in later Cretaceous formations. The same interpretation that was suggested for the Lander section seems reasonable here.

All along the foothills of northern Colorado the Cretaceous section differs from the eastern Wyoming section only in minor details. I have selected as typical the section west of Fort Collins (number 10 of the chart). The Greenhorn limestone is better developed, becoming considerably thicker southward, while the Mowry shale ceases to be recognizable as a distinct unit. In other respects, save for varying thicknesses, the sections of the rocks closely associated with the Dakota are practically identical. The marine shale between the sandstones which have here been referred to the Dakota is well developed and contains, in addition to the fossils collected at Horse Creek, one or two other species of *Inoceramus*, some simple forms of *Ostrea*, and an *Anchura*. This fossiliferous shale with the same small group of species was examined by me in 1906 at many points between Fort Collins and Boulder. Some of the localities near Boulder were visited in company with Prof. Junius Henderson, who has since briefly discussed¹⁵ the horizon and extended its known distribution to the northern boundary of the State. Its faunule has just been described, illustrated, and discussed in a paper by J. B. Reeside, Jr., accepted for publication in the "Shorter contributions to general geology" of the United States Geological Survey.¹⁶

In 1905 I had the privilege of joining W. T. Lee in a field review of a number of localities in southeastern Colorado, northwestern Oklahoma, and northeastern New Mexico where a characteristic Comanche (Washita) fauna¹⁷ is found in beds between two sandstones, both of which have been called Dakota and the upper one doubtless is Dakota. We found *Gryphaea corrugata* and associated Washita forms at Two

¹⁵ Junius Henderson: The foothills formations of north central Colorado. Colorado Geol. Survey, 1st Rept., 1908, pp. 172-178; Colorado Geol. Survey, Bull. 19, 1920, pp. 83-85.

¹⁶ U. S. Geol. Survey, Professional Paper no. 131.

¹⁷ T. W. Stanton: Morrison formation and its relation with the Dakota formation. Jour. of Geology, vol. 13, 1905, pp. 657-669.

Buttes, Colorado, on the Cimmaron at Garrett, Oklahoma, and at many localities in northeastern New Mexico, while farther inland, beyond the range of *Gryphæa*, we found other typical Washita fossils on the Purgatoire River south of La Junta, Colorado. On more slender paleontologic evidence I ventured to identify the same horizon at Cañon City. In the Apishapa quadrangle Stose¹⁸ defined the Purgatoire formation to include the marine shale and the underlying sandstone and conglomerate. The Purgatoire has since been recognized on stratigraphic and lithologic grounds, without definite paleontologic evidence, in the Colorado Springs and Castle Rock folios.

In 1906, with the enthusiasm aroused by the previous season's field-work, I examined many exposures of the Dakota and associated rocks in Colorado, from the Cache la Poudre, above Fort Collins, to Cañon City, in the hope and expectation that a distinctive Comanche fauna would be found, but that hope was not realized. The oysters, *Inocerami*, etcetera, already mentioned, were found at many localities in northern Colorado, but on account of insufficient evidence I was not then and have not since been able to convince myself that they were contemporaries of the Washita species of *Gryphæa*, *Protocardia*, *Trigonia*, *Inoceramus*, etcetera, of the southern Colorado and southern Kansas localities. Possibly they were; but, if so, why did not more of the fauna go north with them? The difference in faunas is apparently not due to difference in salinity of the water, for the northern fauna is as distinctively marine as the southern one. The northern fauna has been recognized as far south as Boulder (about latitude 40°), while the characteristic Washita has not been seen north of the Apishapa quadrangle; so that there is an interval of more than 100 miles along the strike between the limits of their known occurrence.

When sections 9 and 10 of the chart, which are still farther apart, are compared, the obvious suggestion is that the two faunas occupy the same position and are contemporaneous; but that implies the unproved assumption that the overlying and underlying sandstones, respectively, are continuous and contemporaneous throughout the distance between the two sections. A similar comparison of the Cretaceous sections of northern Texas and southern Kansas just as obviously suggests that the sandstone at the base of the Trinity group in Texas is of the same age as the much younger Cheyenne sandstone in Kansas. It seems to me that the evidence is not yet sufficient either to prove or disprove the Washita age of the earliest marine Cretaceous beds of northern Colorado, but I think it more

¹⁸ U. S. Geol. Survey, Geologic Atlas, Apishapa folio (no. 186).

probable that they belong to post-Washita time. Whatever their relations with the Washita may be, it is reasonably certain that they are the same as the lowest marine Cretaceous shale in the Horse Creek section (number 11) and the shale beneath the sandstone bearing a Dakota flora in the Lander, or central Wyoming, section (number 12), and most probably the shale beneath the Newcastle sandstone of the Black Hills section is also of the same age.

It will be remembered that the overlying sandstone in all these sections is not a continuous bed, but varies in thickness from 0 to 60 feet. In regions farther north and west, as around the Bighorn and Little Rocky Mountains, where no such sandstone is identifiable, it seems a reasonable interpretation to correlate an indeterminate lower part of the Thermopolis shale with the lowest marine Cretaceous shale of the northern Colorado and eastern Wyoming sections, since the shales above and below the sandstone are of the same lithologic character and would not be distinguished if they were not separated by the sandstone. If these marine beds are of Washita age, it necessarily follows that all of the Dakota as typically developed in eastern Nebraska and Kansas are also of Washita age, as Twenhofel and others have held; but it has already been shown that the arguments for referring the Dakota to the Washita, so far as they are derived from the distribution of the invertebrate faunas, are based on false premises. The typical Dakota is most probably represented on the west side of the Great Plains not only by the uppermost sandstone of the "Dakota hogback" in northern Colorado and its probable equivalent, the Newcastle sandstone of the Black Hills, but also by the underlying marine shale and probably part of the sandstones beneath it.

Section number 9 of the chart, in the Apishapa quadrangle, southern Colorado, and number 8, at Garrett, Oklahoma, show the same kind of progressive change toward the conditions of the Denison section that is seen in going from central Kansas through southern Kansas to Denison (sections 3, 2, and 1).

NEW MEXICO SECTIONS

Another line of sections running west from Denison, near Tucumcari, New Mexico (number 5), at Canyon Largo, southeast of Las Vegas (number 6), and near Casa Salazar, on Puerco River, northwest of Albuquerque, New Mexico (number 7), show the rapid thinning and disappearance of the Washita in that direction. Its fauna is not found many miles beyond Tucumcari, and at Casa Salazar there are no rocks to represent it. The thin Dakota sandstone, which there rests on the Morrison, is followed by marine shales and sandstones in which a number of faunal

zones are recognizable, including the Niobrara, the zone of *Prionocyclus wyomingensis*, the zone of *Inoceramus labiatus*, and a basal zone whose fauna connects it with the basal part of the Mancos in southern Utah and to a slight extent with the fauna of the Woodbine sand of Texas.

REVIEW AND CONCLUSION

The map (plate 5) shows the location of the sections discussed and indicates the areal distribution of the Kiowa, or *Gryphæa corrugata*, fauna, of the Mentor, or more restricted Washita fauna, and the more or less hypothetical extent of the sea in which the oldest marine Cretaceous deposits of northern Colorado and of Wyoming and more northern regions were laid down.

The paleogeography and history of the Great Plains in Washita and Dakota time can not be correctly interpreted until it is possible to make positive correlations between the well determined Washita of the southern area and the doubtful beds farther north. Grabau¹⁹ has interpreted the Dakota as deposited during a retreat and readvance of the sea, the retreat beginning early in Washita time and the readvance ending in Benton time. It seems to me impossible to adjust the known facts to this hypothesis. The encroachment of the sea on the American continent which inaugurated Trinity (earliest Comanche) time was gradually continued through Trinity and Fredericksburg time, but at the beginning of the Washita the movement was accelerated without any previous reversal and the sea soon reached Kansas and Colorado. I agree with Twenhofel's²⁰ suggestion that it is reasonable to regard the Cheyenne, Kiowa, Mentor, and associated rocks as all deposited during one general transgression of the sea, but I would interpret the Dakota as representing merely a halt in that advance rather than a complete retreat of the sea from the Great Plains area as far south as Texas. The axis of depression in which this irregular advance was made was probably near the western border of the Plains, and from this trough the waters spread laterally as the depression increased. Littoral, lagoon, and swamp deposits were formed along both shores of the comparatively narrow, shallow sea, and locally the two kinds of deposits shifted places from time to time. In my opinion, the sea did not go beyond southern Colorado and central Kansas during Washita time.

If the views here stated are true, it is obvious that there is no proper boundary between two geologic systems either at the base or at the top of

¹⁹ Bull. Geol. Soc. Am., vol. 17, 1906, pp. 620-627. Principles of stratigraphy, p. 739.

²⁰ Am. Jour. Sci., 4th ser., vol. 49, 1920, pp. 289-294.

the Dakota. The relationship with the Comanche in Kansas, southern Colorado, and eastern New Mexico and with the overlying Upper Cretaceous rocks throughout its extent is too intimate. It is true that the Comanche fauna as a whole is very distinct from the Upper Cretaceous fauna as a whole, but the change from the Kiowa or Denison fauna to the Woodbine or from the Woodbine to the Benton shows little if any greater contrast than is found between the Niobrara and Carlile faunas, or between the Carlile and the Greenhorn, or even between some of the zones in the Carlile. And yet these faunal changes within the Upper Cretaceous were certainly not caused by the complete retreat and a succeeding advance of the sea. The restricted distribution of the Woodbine sand and its absence from central and southern Texas suggest an unconformity at the base of that formation or at the base of the Eagle Ford,²¹ but recent workers consider it unimportant if present. Stephenson²² has presented evidence in favor of an erosion interval between the Eagle Ford and the Austin chalk, a suggestion which is also supported by the varying thickness of the Eagle Ford. It is probable, however, that all of these unconformities, so far as they actually exist, represent only local and temporary uplifts whose influence was not felt over a wide area.

The proposal to elevate the Comanche series to the rank of a system, under the name Comanchean, which was made in Chamberlin and Salisbury's *Geology* in 1906, has never seemed to me justified by the facts known at that time, and the arguments then advanced for it have been much weakened by subsequent investigations. Both the physical break and the faunal change at the top of the Comanche now seem much less important. In arguing for the importance of the division, it was assumed that the Comanche series has approximately the same upper limit as the European Lower Cretaceous—that is, the base of the Cenomanian—but many European paleontologists have long referred the Washita to the Cenomanian, and of late the paleobotanists have become insistent on that correlation on account of the character of the flora of the Cheyenne sandstone. I have often stated²³ in print that the Washita may be in part at least Cenomanian, when explaining that “the whole of the Comanche series is treated as Lower Cretaceous, because in the Texan area the top of the Comanche is the only natural and satisfactory major plane of division in the Cretaceous.” Some of those who accept the correlation of the Washita with the Cenomanian and wish to recognize two systems

²¹ University of Texas, Bulletin 1916, no. 44, p. 72.

²² U. S. Geol. Survey, Professional Paper 120, p. 149.

²³ See, for example, *Jour. of Geology*, vol. 5, 1897, pp. 583 and 606; *idem*, vol. 17, 1909, p. 416; U. S. Geol. Survey, Monograph 44, 1903, p. 14.

within the Cretaceous have tried to harmonize the American with the European classification by restricting Comanchean to the pre-Washita rocks. A more artificial systemic boundary could hardly be drawn. No one well acquainted with the Comanche fauna and with the field relations of the Comanche rocks could accept such a boundary between systems, or such a restriction of Comanche, which is now applied to a perfectly natural provincial series.

In southern Texas, on Devils River and on the Pecos, as has been stated by Dumble and other Texan geologists and confirmed by my own field observations, there is a complete lithologic transition from the Fredericksburg to the Washita and a recurrence of the Fredericksburg faunal facies high in the Washita rocks just beneath the Del Rio formation. I refer to the persistence of the Edwards limestone type of lithology in the equivalent of the Georgetown limestone, and the recurrence of the Edwards faunal facies, characterized by certain rudistid and nerinean types, above beds with characteristic Georgetown fossils. Making due allowance for differences in fauna due to littoral, deeper water, and reef facies, all of which are present in the Comanche, the entire Comanche fauna is a unit showing only such progressive changes as are to be expected within a series.

From all these considerations and from others which can not be detailed here, the conclusion is reached that the Comanche series as defined by R. T. Hill is a good provincial series, but in my opinion the term should be restricted to rocks in Texas and Mexico, and to those of adjacent regions that can be strictly correlated with them. Its application as a series term to the Lower Cretaceous of the Pacific coast is not justified by the present state of knowledge, and the recognition of Comanchean as a system of world-wide application is still less justified.

THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS, 1922

President:

CHARLES SCHUCHERT, New Haven, Conn.

Vice-Presidents:

HENRY S. WASHINGTON, Washington, D. C.

ROBERT T. HILL, Glendale, Calif.

W. D. MATTHEW, New York City

T. L. WALKER, Toronto, Canada

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History,
New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1922)

T. W. VAUGHAN, Washington, D. C.

GEORGE F. KAY, Iowa City, Iowa

(Term expires 1923)

L. C. GRATON, Cambridge, Mass.

G. D. LOUDERBACK, Berkeley, Calif.

(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio

BULLETIN

OF THE

Geological Society of America

VOLUME 33 NUMBER 2
JUNE, 1922



JOSEPH STANLEY-BROWN, EDITOR



PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

CONTENTS

	Pages
Theory of Isostasy—A Geological Problem. By William Bowie - - - - -	273-286
Condition of the Earth's Crust and the Earlier American Gravity Observations. By George R. Putnam - - -	287-302
Some Considerations Touching on Isostasy. By H. Q. Wood.	303-316
Isostasy and Earth Movements. By Harry Fielding Reid -	317-326
Isostasy and Applied Geology. By James F. Kemp - - -	327-332
Folding of Mountain Ranges—The Argument from Isostasy. By Sir Sidney Burrard - - - - -	333-336
Isostatic Compensation Considered as a Cause of Thrusting. By Andrew C. Lawson - - - - -	337-352
Weight of Sedimentary Rocks per Unit Volume. By Alfred C. Lane - - - - -	353-370
Role of Isostatic Stress. By Bailey Willis - - - - -	371-374
Isostasy and Rock Density. By Henry S. Washington - -	375-410

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

Subscription, \$10 per year; with discount of 10 per cent to institutions and libraries and to individuals residing elsewhere than in North America. Postage to foreign countries in the postal union, forty (40) cents extra.

Communications should be addressed to The Geological Society of America, 77th Street and Central Park, West, New York City, or care of Florida Avenue and Eckington Place, Washington, D. C.

NOTICE.—In accordance with the rules established by Council, claims for non-receipt of the preceding part of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C., under the Act of Congress of July 16, 1894.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

THEORY OF ISOSTASY—A GEOLOGICAL PROBLEM¹

BY WILLIAM BOWIE

(Presented before the Society December 29, 1921)

CONTENTS

	Page
Introduction.....	273
Extent of isostatic investigations.....	274
Relation of gravity anomalies to topography.....	274
Relation of isostatic gravity anomalies to geologic formation..	275
Isostatic adjustment of delta formations.....	276
Completeness of isostatic adjustment.....	277
Depth of compensation.....	278
Regional distribution of compensation.....	279
Mountain formation by vertical <i>versus</i> horizontal movements	280

INTRODUCTION

It would be inappropriate, at a meeting like this, to consider in detail the accuracy of the geodetic observations on which the investigations in the theory of isostasy are based, and to give detailed accounts of the methods employed in making investigations. Many articles have been published which deal with the geodetic observations and with the isostatic investigations which are, no doubt, familiar to you. They can be consulted by any one wishing to make an exhaustive study of the subject.²

¹ Manuscript received by the Secretary of the Society December 22, 1921.

This paper is one of a series composing a symposium on isostasy.

² John F. Hayford: Figure of the earth and isostasy from measurements in the United States. U. S. Coast and Geodetic Survey, 1909. (No number.)

John F. Hayford: Supplementary investigation in 1909 of the figure of the earth and isostasy. U. S. Coast and Geodetic Survey, 1910. (No number.)

John F. Hayford and William Bowie: Effect of topography and isostatic compensation upon the intensity of gravity. U. S. Coast and Geodetic Survey Special Publication No. 10, 1912.

William Bowie: Effect of topography and isostatic compensation upon the intensity of gravity (second paper). U. S. Coast and Geodetic Survey Special Publication No. 12, 1912.

William Bowie: Investigations of gravity and isostasy. U. S. Coast and Geodetic Survey Special Publication No. 40, 1917.

H. J. Couchman: The pendulum operations in India and Burma. Professional Paper No. 15, Trigonometrical Survey of India.

Sidney Burrard: Investigations of isostasy in Himalayan and neighboring regions. Professional Paper No. 17, Trigonometrical Survey of India.

I shall attempt to show what has been accomplished by the isostatic investigations. I shall also outline some conclusions of a geological nature which seem to be justified.

EXTENT OF ISOSTATIC INVESTIGATIONS

The geodetic data on which the investigations of isostasy have been based are confined largely to the areas of the United States, Canada, and India. Investigations are now under way by geodetic organizations in other countries, and it is hoped that the results may soon appear, in order that we may learn whether isostasy obtains in those countries. At present, it may be said we are extrapolating in regard to the extent to which the condition of isostasy obtains throughout the world. In the first place, less than three-tenths of the surface of the earth is land area, and the United States, India, and the part of Canada where gravity observations have been made comprise only about 10 or 12 per cent of the land surface. It will be seen, therefore, that our investigations in isostasy represent only about 3 per cent of the entire surface of the earth.

While it is true that the isostatic investigations have been confined to rather limited areas, we have within the areas in question a great variety of topography and of geological formations.

RELATION OF GRAVITY ANOMALIES TO TOPOGRAPHY

I think it can safely be said that there is no relation whatever between the character of the topography and the residual deflections of the vertical or the gravity anomalies. This means that the theory of isostasy, as applied in the investigations, is applicable to areas having various elevations. Some of the deflection and gravity stations are at sealevel, with no elevation; others are on the highest mountains, while many are on the intermediate plains and plateaus. When we plot the gravity anomalies and draw curves of equal anomaly, it is impossible from these curves to detect the high and low ground. This condition is in striking contrast to that which obtains with the gravity anomalies based on the rigid-earth theory. When the earth's crust is considered to be rigid, with masses above sealevel as extra loads on the earth's crust, and the deficiency of mass in the ocean an underload, we get anomalies which are very much larger than those by the isostatic theory. The anomalies on the theory of a rigid earth are due to the isostatic compensation which is ignored in the reductions. With a gravity map drawn from these anomalies, it is possible to detect the areas where the ground is mountainous and where it is flat.

RELATION OF ISOSTATIC GRAVITY ANOMALIES TO GEOLOGIC FORMATION

While there is no apparent relation between the character of the topography and the isostatic anomalies, there is a decided relation between certain geologic formations and the isostatic gravity anomalies. It was early found in the investigations of gravity and isostasy that there appeared to be definite relations between the gravity anomalies and the Precambrian and the Cenozoic formations. This relation, first noticed at the beginning of the investigations of gravity and isostasy by Hayford and the speaker, has proved to exist to a very marked degree.

There are now in the United States, Canada, and India 131 gravity stations located on the Cenozoic formation. The average value of the anomaly, without regard to sign, is 0.024 dyne, while the average for all of the stations located in the United States, Canada, and India is 0.021 dyne. The mean anomaly, with regard to sign, is -0.015 dyne, while for all of the gravity stations in the areas in question the mean with regard to sign is -0.006 dyne. Of the Cenozoic stations under consideration, 87 have negative anomalies and only 42 have positive anomalies.

With regard to the Precambrian stations, we have 38 in the United States, Canada, and India. The mean anomaly without regard to sign is 0.022 dyne, while the mean with regard to sign is $+0.006$ dyne. Of the 38 Precambrian stations, 27 have positive anomalies and only 11 have negative anomalies. It was thought for some time, especially by the opponents of the theory of isostasy, that the presence of the large anomalies on the Cenozoic and Precambrian formations were indications of the strength of the earth's crust, and that they indicated the magnitude of the departures from a perfect isostatic state.

The speaker, in his investigations, reached the conclusion that the Precambrian and the Cenozoic gravity anomalies did not indicate a departure from the isostatic condition, but that the persistence in sign is an indication of the effect of the light material of the Cenozoic formation close to the station, or of the extra heavy material of the Precambrian formation close to the station, and that probably the columns under these formations are normal in mass, the light material or heavy material being compensated by material heavier or lighter than normal and lower in the isostatic shell.³

This view has gained favor during the last few years and has received very strong indorsement from Sir Sidney Burrard, former Surveyor-

³ William Bowie: Investigations of gravity and isostasy. U. S. Coast and Geodetic Survey Special Publication No. 40, p. 70.

William Bowie: Our present knowledge of isostasy from geodetic evidence. *Journal of Geology*, July-August, 1917, pp. 422-445.

General of India. In professional paper number 17 of the Trigonometrical Survey of India, entitled "Investigations of isostasy in Himalayan and neighboring regions," Burrard reviewed the literature dealing with the negative anomalies at gravity stations located on the Cenozoic formation in India, especially the Indo-Gangetic plain, and outlined briefly the attempts which had been made to explain the persistent negative sign. In this book he quotes from special publication number 40 of the United States Coast and Geodetic Survey, as follows:

"In India there is a broad belt of recent geologic material running approximately east and west at the foot of the Himalaya Mountains. The stations on the recent formation, which no doubt is largely due to the deposition of materials eroded from the mountains, have in general negative anomalies. It is impossible that the addition of materials could make the pressure less than normal on the surface at the depth of compensation. We may therefore conclude that isostatic adjustment probably follows the deposition of materials, and that the negative anomaly is probably due to the lighter materials in the upper crust."

Following this quotation from special publication number 40, Colonel Burrard said:

"In consequence of Bowie's contention that the negative anomalies are evidence of the isostatic compensation of the Gangetic trough, I have lately made a series of calculations to test the correctness of this view. Although in the past I had never been able to perceive any strong geodetic evidence either for or against the isostatic compensation of the trough, I am now of the opinion that Bowie's contention is probably correct; for reasons which I will subsequently explain, I consider that the evidence available favors the view that the Gangetic deposits are compensated."

Burrard also stated in his book that he agreed with the speaker that it may be possible to ascribe the negative gravity anomalies to the Cenozoic formation.

ISOSTATIC ADJUSTMENT OF DELTA FORMATIONS

Delta formations have been held by some geologists to be evidence of the ability of the earth's crust to withstand heavy loads.⁴ But such evidence as we have at hand indicates that values of gravity on delta-formation areas are as nearly normal as the values of gravity stations on the Cenozoic material, which is inland from the coast, such, for instance, as the Indo-Gangetic plains. Wherever we have gravity stations on deltas,

⁴ Joseph Barrell: The strength of the earth's crust. *Journal of Geology*, vol. xxii, no. 1-8, 1914; vol. xxiii, nos. 1, 5, and 6, 1915.

Bailey Willis: Discoidal structure of the lithosphere. *Bull. Geol. Soc. Am.*, vol. 31, no. 2, June, 1920.

the gravity anomalies tend to be negative in sign and are of about the average size of the anomalies on other Cenozoic material.

If we assume that the density of the delta material is about 2.2, it is evident that the material now occupying the volume once occupied by the water is 2.2 times as heavy as the water which formerly occupied the space. If this added mass were an overload on the earth's crust, then we should certainly expect the gravity anomalies to be positive, owing to the increased attraction of the added material. The fact that the gravity anomalies tend to be negative and often large would indicate that there is considerable depth to the delta deposits, and that probably the column under the delta formation has normal mass and is in isostatic equilibrium. This question of the delta material and the strength of the earth's crust is treated in a paper⁵ by the speaker which has recently appeared.

Of eight gravity stations recently established by the Coast and Geodetic Survey on or very near to the delta of the Mississippi River, four have negative and four positive anomalies. The average of these anomalies with regard to sign is -0.006 . If we include the station at New Orleans, previously established, the average is -0.008 . This is evidence against the Mississippi Delta's being an uncompensated load.

COMPLETENESS OF ISOSTATIC ADJUSTMENT

If we find that there is no relation between the topography and the deflections of the vertical or gravity anomalies, and if we can give a rational interpretation of the sizes and signs of the anomalies found on the Cenozoic and Precambrian formations, and if there is no definite relation between the signs and sizes of the anomalies and other geological formations, are we not justified in assuming that, as far as the areas covered by the investigations are concerned, they are in a state of equilibrium, and that isostasy within those areas is nearly perfect? It would also seem to be reasonable for us to assume that other areas which have not been included in our investigations, but which in their topographic features and geologic formations are similar to the United States, Canada, and India, are also in isostatic equilibrium. It may be that we would also be justified in assuming that the crust under the ocean area is in equilibrium. It is possible that we are assuming too much in this, but it is the speaker's belief that when we shall have perfected an apparatus for the accurate determination of gravity at sea, we shall find the ocean areas in about the same degree of isostatic equilibrium as is found for the land areas.

⁵ William Bowie: The relation of isostasy to uplift and subsidence. *American Journal of Science*, vol. ii, July, 1921.

DEPTH OF COMPENSATION

In our isostatic investigations we have assumed uniform distribution of isostatic compensation with respect to depth. This was done for two purposes: In the first place, to make it possible to carry on the great amount of work involved in computing the topographic effect on the plumb line and on the pendulum, and in the second place because uniform distribution is a mean of all the possible methods of distribution. We do not, of course, feel that the compensation is exactly uniformly distributed, but it is probable that, no matter what the distribution may be, the effect on the geodetic data would be about the same as uniform distribution. At least the uniform distribution has had a remarkable success in eliminating deflections of the vertical and in reducing gravity anomalies without leaving any apparent relation between the topography and the residuals.

From the investigations involving the deflections of the vertical and isostasy and those dealing with the values of gravity and isostasy, depths of compensation have been derived. The depth of compensation is a term used to indicate that there is a surface concentric with sealevel below which there is no isostatic compensation. It is not probable that the depth of compensation is a definite surface, nor is it probable that the compensation extends always to the same surface or zone. It is certain that we do have somewhere below sealevel such changes in the conditions of temperature and pressure that the material of the crust is transformed from a resisting to a yielding mass.

We have a horizontal movement of the material somewhere below the surface of the earth's crust which tends to maintain the equilibrium between blocks of the isostatic shell. It is well known that tens of thousands of feet of material have been eroded from mountain areas and deposited at low altitudes. The gravity results and the deflections of the vertical show that areas of erosion and areas of deposition are approximately in equilibrium, and therefore we must have had transference of material from the column under the sedimentary area back to the column under the area of erosion. The question is, Where does this flow take place?

The material of the earth's crust offers great resistance to horizontal movements within it, although it yields vertically rather easily to loads that are laid down on its surface. If the material of the crust itself were plastic to horizontal forces, we might expect mountain masses to overflow surrounding plains and the continents to flatten out into the ocean bottoms. This does not happen. It is reasonably certain that the material

of the crust does not yield horizontally to any marked degree under the stress differences between high columns and low ones until the depth of compensation has been reached. Below the depth of compensation, the material must yield horizontally to rather low stress differences acting for long periods. It is readily understood that the stress difference is from a column of the isostatic shell under a mountain area toward a column under the adjacent plain until we have reached the lower surface of the isostatic shell.

It is hardly probable that the temperature and pressure conditions of the plastic material differ much at various places, and therefore we may assume that the depth of compensation does not vary materially from place to place. It is possible that the depth below sealevel of flow is somewhat greater under oceans than under continents, owing to the shorter columns.

REGIONAL DISTRIBUTION OF COMPENSATION

In making the computations involved in the isostatic investigations, it was assumed that every topographic feature was compensated by a deficiency or an excess of density in the earth's crust directly beneath it, even to the extent of having the compensation confined to a column that is only a fraction of a square mile in cross-section. No advocate of isostasy would agree that it is possible to have each small column compensated independently of surrounding regions.

A test was made and reported on in special publication number 40 of the United States Coast and Geodetic Survey, to show whether regional distribution of isostatic compensation is more reasonable than the local compensation. It was found that the gravity anomalies were reduced as effectively by regional distribution of compensation out to a distance of 36 miles from the station as by local compensation; but when the compensation was distributed to a distance of 100 miles from the station, the gravity anomalies became systematic in their appearance and it was found that there was a definite relation between the elevation of the station and the gravity anomaly. It is reasonably certain that there is no strictly local distribution of the isostatic compensation, but it is equally improbable that the compensation is distributed for great distances from the topographic features. After consideration of the resistance to vertical movement by a column of the isostatic shell, the speaker believes that the column which may be in isostatic equilibrium, independently of the surrounding areas, is of the order of magnitude of one square degree at the equator, or about 70 miles square.

There has been diversity of opinion as to the size of the topographic feature which might escape compensation. This subject has been much confused by the fact that there has not been made a clear distinction between the horizontal extent of the topographic feature which may escape compensation and the cross-section of the column of the isostatic shell which may be in equilibrium independently.

A test was recently made of the mass which might escape compensation and the results have appeared in one of the papers⁶ of the speaker. This test shows that for stations at high elevations the compensation of the surrounding topography can not be ignored to any great extent without having a very marked effect on the gravity anomalies.

When the compensation of the topography for a disk with a radius of about 18 miles and 3,000 feet in thickness was ignored, the gravity anomalies became much larger than they were when all the topography was considered to be compensated, and 37 of the anomalies at the 42 stations used had negative signs. When the area of the disk was given a radius of about 36 miles, the anomalies were still further increased in size and all of them except one had the negative sign.

The conclusion from this test would seem to be that a disk of material 3,000 feet in thickness and 18 miles in radius is largely compensated. Considering the mass above sealevel forming a continent, this amount of topography is very small.

The compensation of this disk 3,000 feet in thickness and 18 miles in radius is probably not directly under the material, but is distributed somewhat regionally.

After a consideration of this test, made to show the size of the topographic feature which may not be compensated, we are led to the conclusion that a mountain system certainly does not escape compensation.

It should be recognized that the mountains and the oceans are not compensated by a deficiency of density under the land and an excess of density under the oceans, but that the landmasses compensate the deficiency of density in the isostatic shell below them and the deficiency of mass in the oceans compensates the excess density below the oceans. The landmasses and deficiency in the oceans are the effect rather than the cause of the isostatic compensation.

MOUNTAIN FORMATION BY VERTICAL *versus* HORIZONTAL MOVEMENTS

If we accept isostasy as substantially true, and it would seem to be very logical that we should do so after considering the geodetic evidence and

⁶ Some geologic conclusions from geodetic data. *Proceedings of National Academy of Sciences*, vol. 7, no. 1, January, 1921, pp. 23-28.

the results of the isostatic investigations, then we are justified in concluding that probably the earth's crust has been in the same condition of isostatic equilibrium throughout geological ages. We can not conceive of the physical conditions of the earth's material being very different since the earliest geological record.

If we have had the isostatic condition throughout geological times, then we are forced to the conclusion that mountain masses have never been extra loads on the earth's crust, and therefore that they are not due to regional horizontal forces sending the earth's material into great elevations. If we can not have mountains formed by horizontally acting forces, then we are compelled to accept the theory that they are due to local vertical forces and movements.

As mountain systems have always been formed in areas which were previously occupied by heavy sediments, there must have been a change in the density of material during the process of mountain uplift. Do we not have here the key to the situation? We know that the density in the earth's crust is a function of the elevation of the surface, and we know that this surface has changed greatly in elevation from one geological period to another, and that, in the process of changing a density to a smaller one, movement must take place. We have here, I believe, the cause of the uplift, which is the lengthening of the column under the sedimentary material, as the material expands and decreases its density.

Distortion of the sedimentary strata of the earth's crust has generally been held to be largely due to regional horizontal forces. It would appear that much of this distortion could be caused by vertical movements. Sedimentary matter is generally deposited in a very irregular way. As material is deposited in different parts of a region at different times and at different rates, we should expect a great amount of distortion of the sedimentary strata and also of the material at the base of the sediments during the period of sedimentation. The greatest distortion of the material would probably be near the edges of the sedimentary area where resistance to settlement would be greatest.

When sedimentation of a region has ceased, then there is probably a period of quiescence and later of uplift. During the uplift the region will undoubtedly rise in different places at different times and rates. As a result of this irregular upward movement, we should expect a great amount of distortion of the recent sedimentary material and also of the material on which the sediments had been laid. During this process of uplift it is probable that at some places there would be developed forces which would be inclined to the vertical, and in some cases they might be even horizontal.

There is much distortion of the material of the earth's crust during the isostatic adjustment of an area of active erosion. In order to maintain equilibrium in any particular area that is undergoing erosion, material equal in mass to that eroded must be brought into the lower part of the column. It is probable that the material brought into the column is as much as 10 per cent heavier than that eroded from the surface. Let us assume that the difference is exactly 10 per cent. Then as a certain thickness of material is eroded from the surface, the elevation will be lowered by about 10 per cent of the thickness of the disk that has been removed. It is possible that a mountain area may have 30,000 or 40,000 feet of material eroded before the area is baseleveled.

The reason that the magma is exposed in the older mountains is that, as erosion takes place, the mountain area is maintained approximately in its elevation, thus permitting long-continued erosion of the sedimentary material from the area.

During the process of uplift of the material of the column under the eroded area due to the isostatic adjustment, there will be distortion of the material which is sufficiently plastic to yield under the vertical stresses acting on them. There will be fracture of material close to the surface that is so weak as not to be able to resist the movement and at the same time not sufficiently plastic to yield without fracturing.

It is probable that many earthquakes are due to the process of isostatic adjustment, which tends to maintain the elevation of a mountain area as erosion continues and which causes the earth block under an area of deposition to subside. This point was discussed by Reid some time ago in his article entitled "Isostasy and mountain ranges."⁷

The geodetic evidence is sufficient to justify us in eliminating regional horizontal thrusts as the cause of the uplift of the mountain area, and the geodetic data are also such as to make us feel that the downwarping or subsidence of an area that is being sedimented can not be due to regional horizontal thrusts. The evidence would appear to justify our holding that mountains are caused by an actual decrease in the density in the column under them, and that the elevations of mountains, after erosion begins, are approximately maintained by the isostatic adjustment which brings material into the column under the mountain area. The subsidence of a surface in an area of sedimentation is probably due both to the load of sediments and to an actual contraction of the material of the column.

If we have been successful in eliminating regional horizontal thrusts as the cause of the uplifting of mountain areas, then we must seek for

⁷ Proceedings of American Philosophical Society, 1911, pp. 444-451.

the cause of the uplift by vertical movements. The speaker discussed this subject in two papers which have recently appeared.⁸

Of course, it is not known what is the real cause of a change of density in a column under a sedimentary area, but by a process of elimination we have left, as a possible cause, the great change in temperature which must take place as the sediments are increased in thickness. We have evidence that areas have had as much as 30,000 or 40,000 feet of sediments laid down on them in one geological age. Let us assume a thickness of 30,000 feet, or about six miles. All of the sediments undoubtedly were deposited at an elevation very little different from sealevel. This means that, as the sediments were laid on, the block of the earth's crust under them sank deeper into the earth. Most of the material of the block was lowered approximately to the extent of the depth of the sediments over it, and consequently the material lowered would be raised in temperature by an amount equal to the difference in temperature for the change in depth. It is not known what the temperature gradient is below the outer 7,000 feet of the earth's material, but if we have for the first 60 miles or so of the earth a temperature gradient equal to what we find near the surface, the difference in temperature for a six-mile change in depth would be approximately 300 degrees centigrade.

If no increase in temperature occurred in the material of the block until after sedimentation had ceased, then the geoisotherms would have been depressed to the extent that the material in the block went down. The geoisotherms would eventually rise to their normal positions through the depressed block and the change in temperature would undoubtedly have some effect, physical or chemical, or a combination of both, on the material, which might expand it sufficiently to cause uplift at the surface, thus transforming a surface of sedimentation approximately at sealevel into an area of uplift thousands of feet in elevation. It is probable that there is a tendency for the geoisotherms to maintain their normal depths below sealevel during the process of erosion and subsidence, but when we consider that the area of erosion may be 100 or 200 miles in width and many miles in length, we are inclined to believe that there is a considerable lag in temperature of the subsiding column. It is true, of course, that the material below the bottom of the column and at its sides will tend to give off its heat to the colder subsiding material, but this process will tend to cool the sides and bottom material and thus retard the passage of heat from the bottom and sides to the subsiding column. The

⁸ The relation of isostasy to uplift and subsidence. *American Journal of Science*, vol. 2, July, 1921.

Some geological conclusions from geodetic data. *Proceedings of National Academy of Sciences*, vol. 7, no. 1, January, 1921, pp. 23-28.

speaker believes that the geotherms are considerably depressed as sedimentation progresses, although he has no experimental evidence that would lead him to this conclusion.

The change of density could not possibly be due only to the usual thermal expansion of the material. If the material of the column had the cubical coefficient of expansion of 0.000038 per degree centigrade and was raised to a temperature 300 degrees centigrade higher than it had before, we should expect an elevation of the surface of only about 3,500 feet if the column is 60 miles in length.

If we assume that an area has been elevated to an average of 9,000 feet, an increase of about 3 per cent in the length of the column of 60 miles must have occurred. It is seen that there must have been some other process taking place in the column under a sedimentary area than merely thermal expansion, and this process possibly is a physical or chemical rearrangement of the elements of the material resulting in a decrease in density.

As erosion continues in an uplifted area the isostatic balance of the block below the area is maintained by a horizontal flow of material into the block at its lower end. This inflowing material is undoubtedly denser than the material eroded from the surface. Let it be assumed that the density is exactly 10 per cent greater. Then as 1,000 feet of material is eroded from the surface a disk only about 900 feet thick is brought into the column, and in consequence the surface has been lowered 100 feet. It is seen from this that, in order to baselevel a mountain system, far more material must be eroded than that represented by material which is above sealevel when erosion began. In order to lower an area 5,000 feet, approximately 50,000 feet of material has to be eroded from the area, on this assumption. It has puzzled geologists in some of their investigations to account for the vast amounts of deposits over a very large area during a single geological formation; but when we realize that perhaps ten times as much material is eroded from a mountain area as is represented by a change in the average elevation of the area, we see that it is not so difficult to understand the source of the sedimentary material.

As the isostatic adjustment continues with erosion, the block under the area of erosion is raised a number of miles above its former position—that is, each particle of the block will have been elevated an amount approximately equal to the total thickness of the material which has been eroded. Let us assume that there have been six miles of material eroded from a mountain area, while the elevation of the surface has been depressed about 3,000 feet. Then the particles of the block, on an average, have been raised above their former position to the extent of about six

miles. This will mean that each particle is brought into a zone which is colder than the one it formerly occupied. If we assume the same temperature gradient as before, we shall have a change in temperature of each of the particles of the column under the area of erosion of about 300 degrees centigrade. It is hardly probable that the geoisotherms maintain their normal depths below sealevel during the process of uplift. The only way that the material of the block can lose its heat is at the surface and at the sides of the rising block. Undoubtedly, there is some cooling of the material of the rising block as erosion takes place, but it seems probable that the geoisotherms are far above their normal positions at the time erosion ceases. When erosion has ceased and there is a period of quiescence, the geoisotherms would, undoubtedly, return to their normal position through loss of heat at the surface and to a certain extent at the sides of the block. During the process of this change of temperature, there would be a thermal contraction of the material of the block which would change its length by approximately 3,500 feet if the cubical coefficient of expansion of the material of the block were 0.000038 per degree centigrade and if the difference in temperature were 300 degrees centigrade. Whether this is all of the contraction that occurs in a block under an area of erosion after erosion has ceased is, of course, not known, but it would seem to be logical to conclude that contraction is also occurring from some other cause than thermal contraction, which will make the surface of the area sink to sealevel or even below.

It is probable that contraction of a column that was once under an elevated area continues by loss of heat and some other process during the time that sediments are being placed on the area. It is the speaker's belief that this contraction of a column under an area of former active erosion is a factor in determining the position at which sediment is deposited subsequently. There seems to be a cycle by which we have uplift and erosion in one area with a downwarping and sedimentation in another area not far distant, followed by baseleveling and contraction of the column under the erosion area and an expansion and uplift of the column under the sediment. Areas of erosion and sedimentation have changed places in the past and it would appear possible that this change takes place continuously. It is understood that the Alps have been a region of erosion and of sedimentation several times; also that the Appalachian system has been an area of elevation and an area of sedimentation more than once. It may be that the change of temperature in a block that is sinking under sediments and another block that is rising under erosion may not be the real cause of the expansion in one case and the contraction in another, but at least we have the processes which are competent

to make some change, and this is far better than many of the older geological theories regarding uplift and subsidence which had no apparent cause for the change.

Aside from the geodetic evidence against regional horizontal forces acting to throw up mountains, we must consider that the material in mountain areas which show horizontal movements is usually quite thin. A layer of material a mile in thickness is about the maximum that we might expect to find. With material of such thinness, being merely a veneer on the earth's crust, we should not expect sufficient strength to justify the idea that the movement has been due to forces acting through hundreds of thousands of square miles of area outside of the mountain region. Such thin material would certainly buckle locally rather than transmit stresses for great distances. This material is frequently warped in the areas outside of the mountains, and therefore any tendency of a regional horizontal force to act through this thin disk would undoubtedly cause it to buckle locally and not to transmit the force necessary to cause distant uplift. In addition, the force would have to overcome the tremendous resistance to shear between this thin veneer and the material of the earth's crust below it.

An analysis of the mechanics of the problem shows so many reasons why regional forces can not be the cause of distortion that we must abandon the whole theory of regional horizontal thrusts and accept one that is in closer harmony with the data available and that will not conflict with the usual processes of mechanics.

Reid⁹ some years ago, and recently Burrard,¹⁰ concluded that the theory that mountains are caused by regional horizontal forces is not in accord with the theory of isostasy.

There is evidence that there are many places which have been uplifted or depressed by very small amounts in comparison with the movements that have occurred in mountain areas. In fact, there is scarcely any part of the earth's surface that has not been elevated or depressed, relative to the position held at some former geological period. These movements, while of very much less importance than the great movements caused in areas of heavy sedimentation and mountain uplift, are nevertheless important from a geophysical and geological standpoint and should be considered. But the principal thing is to arrive at some definite conclusion in regard to the cause of the larger vertical movements.

⁹ H. F. Reid: Isostasy and mountain ranges. *Proceedings of American Philosophical Society*, 1911, pp. 444-451.

¹⁰ Sidney Burrard: On the origin of mountains. *Geographical Journal*, September, 1921.

CONDITION OF THE EARTH'S CRUST AND THE EARLIER AMERICAN GRAVITY OBSERVATIONS¹

BY GEORGE R. PUTNAM²

(Read in full before the Society December 29, 1921)

CONTENTS

	Page
Introduction.....	287
Development of the theory of isostasy.....	288
The transcontinental gravity measurements of 1894.....	290
Hayford's reduction of gravity observations.....	290
The gravity reductions of 1895 compared with earlier and later methods.	291
Comparison of results for regional or local compensation.....	299

INTRODUCTION

The known facts as to the earth and its structure, beyond the knowledge derived from what is visible on its surface, are comparatively few. Its general shape has been determined and its principal dimensions and the proportion of flattening measured. The mean density has been computed. Increasing temperature below the surface has been observed. The interior of the earth is estimated to be more rigid than steel, but it yields to great forces. Its elasticity is observed in earth tides and in the transmission of earthquake shocks. Volcanic craters, geysers, and other outlets give information as to subsurface activities and materials. Earthquakes afford some measure of the more violent adjustments of the crust. The earth is a great magnet.

The greatest depth to which man has penetrated is but 7,579 feet, about 1/2700th part of the earth's radius. This limitation and the meager knowledge of the planet most important to man render of special interest any observational means of studying the conditions below the surface. As a by-product of trigonometrical and geodetic surveys of wide extent, planned to determine the size and shape of the earth and to form

¹ Manuscript received by the Secretary of the Society December 15, 1921.

This paper is one of a series composing a symposium on isostasy.

² Introduced by William Bowie.

a groundwork for extended mapping operations, two instrumental means have been developed of investigating the condition of the earth's crust. Anomalies in the relative direction of the plumb-line may be measured by comparing astronomical positions on the earth's surface with positions derived from triangulation, and anomalies in the force of gravity may be determined relatively by measurements of the vibration periods of pendulums. These anomalies evidently have a common cause, and attention was first called to them by observed deflections in the plumb-line.

DEVELOPMENT OF THE THEORY OF ISOSTASY

The study of these so-called anomalies has furnished evidence, believed to be conclusive, of another fact as to the earth—that the crust, or outer portion, is in a condition of approximate equilibrium, termed isostasy. While the general shape of the earth is that of an oblate spheroid, the actual surface departs from that shape by reason of the irregularities due to the topography, such as mountain ranges, valleys, ocean basins, etcetera. While these surface irregularities are small compared with the dimensions of the earth, yet if the crust were of a uniform density and reached to a uniform depth below sealevel, they would represent enormous inequalities in the loads borne by the strata below. The materials of which the earth is composed could not in general withstand such differences in pressure. Under the isostatic theory, substantially equal weights are sustained on equal areas at some depth below sealevel, this depth not necessarily being uniform. Mountains and other elevated regions are, as it were, floated by lighter materials beneath or composing them, as compared with the materials beneath ocean bottoms, which regions are depressed by reason of their greater density, the extent and arrangement of the differences of density being sufficient to bring about an approximate state of equilibrium.

Although there had been earlier suggestions of this nature, particularly by Herschel in 1837 and Stokes in 1849, the idea of isostasy appears to have been expressed first by Airy. In the triangulation of India the fact was developed that at stations nearest to the Himalayas the plumb-line was deflected toward the mountains, but to a much less extent than would be required by the computed effect of the great mountain masses above sealevel, the discrepancy amounting to about 10 seconds in latitude. The explanation first proposed by Pratt was that this discrepancy is due to an abnormal ellipticity of the earth for this region. Shortly thereafter, in 1855, in a paper before the Royal Society of London, Airy gave his conclusion that the apparent anomaly in India is due to the

earth's crust being in a condition analogous to hydrostatic equilibrium, saying:

"I conceive that there can be no other support [for an elevated tableland] than that arising from the downward projection of the earth's light crust into the dense lava; the horizontal extent of that projection corresponding rudely with the horizontal extent of the tableland, and the depth of its projection downwards being such that the increased power of flotation thus gained is roughly equal to the increase of weight above from the prominence of the tableland. . . . This fluidity [of the interior of the earth] may be very imperfect; it may be mere viscosity; it may even be little more than that degree of yielding which (as is well known to miners) shows itself by changes in the floors of subterranean chambers at a great depth when their width exceeds 20 or 30 feet; and this yielding may be sufficient for my present explanation. . . . The diminution of attractive matter below, produced by the substitution of light crust for heavy lava, will be sensibly equal to the increase of attractive matter above. In all the latter inferences it is supposed that the crust is floating in a state of equilibrium. But in our entire ignorance of the *modus operandi* of the forces which have raised submarine strata to the tops of high mountains, we can not insist on this as absolutely true. We know (from the reasoning above) that it will be so to the limits of *breakage* of the tablelands; but within those limits there may be some range of conditions either way."

The idea of isostasy was here distinctly expressed by Airy, but with an arrangement of compensation now considered improbable.

In a paper³ on this subject in 1859 Pratt agreed that the compensating cause must be looked for in deficiency of matter below the mountain mass, but proposed a different hypothesis:

"At the time when the earth had just ceased to be wholly fluid, the form must have been a perfect spheroid, with no mountains and valleys nor ocean-hollows. As the crust formed, and grew continually thicker, contractions and expansions may have taken place in any of its parts, so as to depress and elevate the corresponding portions of the surface. If these changes took place chiefly in a vertical direction, then at any epoch a vertical line drawn down to a sufficient depth from any place in the surface will pass through a mass of matter which has remained the same in amount all through the changes. By the process of expansion the mountains have been forced up, and the mass thus raised above the level has produced a corresponding *attenuation* of matter below. This attenuation is most likely very trifling, as it probably exists through a great depth."

In 1865 a series of pendulum observations of the force of gravity was made in India, some at high altitudes, and from these conclusions were drawn, first, that the force of gravity "is very much less on the summit of the highly elevated Himalayan tablelands than can be accounted for

³ Phil. Trans. Royal Society, vol. 149, p. 747.

otherwise than by a deficiency of matter below; secondly, that it increases as the ocean is approached, and is greater on islands than can be accounted for otherwise than by an excess of matter below.”⁴

In 1889 Dutton proposed the word *isostasy* for this condition of equilibrium in the earth's crust:

“If the earth were composed of homogeneous matter its normal figure of equilibrium without strain would be a true spheroid of revolution; but if heterogeneous, if some parts were denser or lighter than others, its normal figure would be no longer spheroidal. Where the lighter matter was accumulated there would be a tendency to bulge, and where the denser matter existed there would be a tendency to flatten or depress the surface. For this condition of equilibrium of figure, to which gravitation tends to reduce a planetary body, irrespective of whether it be homogeneous or not, I propose the name *isostasy*.”

THE TRANSCONTINENTAL GRAVITY MEASUREMENTS OF 1894

In 1894 the writer made a series of measurements of the force of gravity at stations which were favorably located for developing information as to the problems of the earth's crust; it was the first extensive series in the United States planned for this purpose, and included a station, Pikes Peak, on one of the Rocky Mountain summits, and others on the western plateaus and in the valleys, the geyser regions, and extending from the Atlantic coast across the Appalachian Mountains and the central plains. The work was initiated by T. C. Mendenhall, then Superintendent of the Coast and Geodetic Survey, and in it the first extensive use was made of the portable pendulum apparatus developed under his direction. The expedition has an added interest to geologists from the fact that Gilbert took part in it by making geological examinations about many of the stations and by discussing the results.

I will recur to the results of this work⁵ and the methods of reduction used.

HAYFORD'S REDUCTION OF GRAVITY OBSERVATIONS

In 1909 Hayford developed a method of reducing observations of the force of gravity taking account, for the first time, of the attraction of all

⁴ Walker: *Nature*, vol. xxxii, p. 486.

⁵ The methods developed at this time permitted a considerable increase in rapidity of field-work. The accuracy of the apparatus and methods and the constancy of the pendulums are indicated by the fact that the mean periods of the three pendulums, A⁴, A⁵, and A⁶, determined by the writer at the base station in Washington on 13 occasions from 1894 to 1900, had an extreme range of but eleven ten-millionths of a second. During this interval the relative force of gravity was determined by the writer at 50 stations, including points in Greenland and Alaska and at the base stations in Europe, and the same set of pendulums was transported approximately 50,000 miles.

the outer portions of the earth's crust and of the curvature. This was an important advance. He had previously applied the same methods to the study of plumb-line deflections. As the force of gravity at any point on the earth's surface depends on the summation of the attractions of all the particles of the earth's mass, as well as the centrifugal force, the mathematical problem of computing a theoretical value of gravity to compare with the observed value was one of considerable magnitude, and to bring it within the range of practicability Hayford made a number of assumptions,⁶ as follows: That the earth's crust is in a state of perfect isostasy, with each topographic feature, however small, compensated for by a deficiency or excess of mass directly under it; that this compensation is uniformly distributed from the surface to a depth of 113.7 kilometers (70.6 miles) below the surface, and that the mean density of the solid portion of the earth's crust is 2.67. It was stated that it was not believed that any one of these assumptions is exactly true. In the original reports and in subsequent papers by Bowie, each of the assumptions is studied and alternate results given for possible variations. This work constitutes the most thorough study that has been made of the results of the determinations of the relative force of gravity as bearing on the problems of the condition of the earth's crust. Aside from the strengthened proof which it affords of the truth of the isostatic theory of the crust, it also develops local and regional anomalies which are probably more significant than any heretofore. Nevertheless the authors do not claim that the comparative smallness of the residuals affords proof of the complete correctness of any one of the assumptions made.

THE GRAVITY REDUCTIONS OF 1895 COMPARED WITH EARLIER AND LATER METHODS

To obtain a comparison between the observed and theoretical value of the force of gravity, the observations of 1894 were reduced to sealevel by three methods, depending on different conceptions as to the condition of the earth's crust.⁷ It appears useful now to briefly review these reductions and the results, in the light of the methods since developed of applying the isostatic compensation corrections.

1. *The Bouguer, or no compensation, reduction* was the original of the three methods, and the other two are based on this. Bouguer's reduction was on the theory of an uncompensated earth's crust, and the attraction of the topography above sealevel was subtracted from observed gravity.

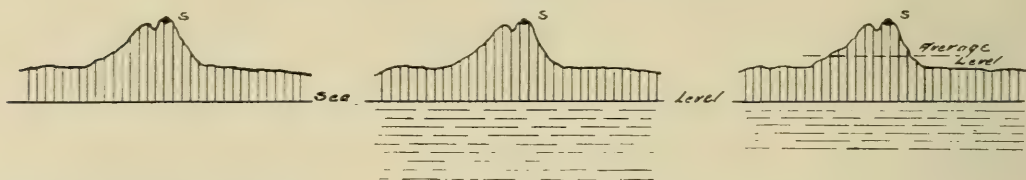
⁶ Coast and Geodetic Survey Special Publication No. 10, 1912, p. 10.

⁷ Report Coast and Geodetic Survey, 1894, App. No. 1. Phil. Soc. of Washington, vol. xiii, 1895, p. 31.

This attraction was computed as that of an indefinitely extended horizontal plate of average surface density and of thickness equal to the elevation of the station, with a correction added, where necessary, for the departure of the surface about the station from a plain. Another term in this reduction corrected for elevation above sealevel.

2. *The free air* (elevation only) *reduction* simply omitted the attraction term in the Bouguer formula. This was done on the theory that the material above sealevel was balanced by a deficiency below. In the terms of compensation, however, omitting the attraction term is equivalent to

For station above the average level

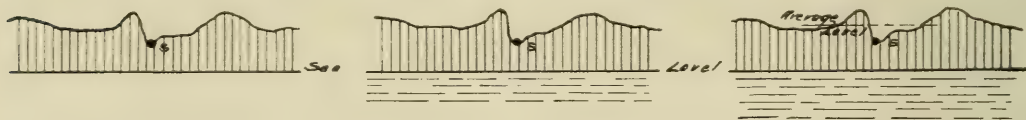


1. Bouguer reduction; no compensation.

2. Free air reduction; compensation for station elevation, showing *over* compensation.

3. Average elevation reduction (1895); compensation for average elevation.

For station below the average level



1. Bouguer reduction; no compensation.

2. Free air reduction; compensation for station elevation, showing *under* compensation.

3. Average elevation reduction (1895); compensation for average elevation.

FIGURE 1.—Diagram illustrating three Methods, used in 1895, of Reduction of Gravity Observations to Sealevel, for two Stations, located one above and one below the average Elevation.

In these examples the average elevation is the same for the two stations. The vertical scale is exaggerated to emphasize the compensation effects. If drawn the same as the horizontal scale, a better idea would be given of the attraction correction. The compensation (shown by horizontal lines) is, for convenience, placed immediately below sealevel, and of depths equal to the station elevation and the average elevation respectively.

introducing a compensation term of equal amount and opposite sign; in other words, a compensation correction equivalent to the attraction of an indefinitely extended horizontal plate whose thickness is the elevation of the station and of average surface density, or the equivalent of this. This method resulted in excessive compensation for stations above the average level and deficient compensation for stations below the average level (as shown in the diagram), and large corresponding anomalies resulted in mountainous regions. For a station at the summit of a peak, for example, the surrounding region was compensated as though it were all at the elevation of the peak, evidently an over compensation for the region in

general, and this over compensation resulted in a positive difference, observed minus theoretical force of gravity. Under either a regional or a local idea of compensation, the over compensation of the region surrounding a station will result in a positive gravity anomaly. There has been some misconception as to this free air reduction. It is based on the theory of isostasy and takes account of both the attraction of the topography and of its compensation; but it does this only in a general way, and when it is applied to summit and valley stations there is no theory to justify it. It has been stated that it assumes that "each piece of topography is compensated for at zero depth" and also "a very plastic crust." A conception of compensation as located vertically beneath a station and affecting gravity only at that station and not in the surrounding regions is evidently an impossible hypothesis and one that is not called for by the free air reduction formula.

3. *Average elevation reduction.*⁸ The large residuals resulting from the Bouguer reduction showed the incorrectness of the hypothesis of uncompensated topography above sealevel. The disappearance of these large residuals at stations in level regions or near the average elevation with the free air reduction was proof of a general condition of isostasy, but the residuals remained still large for stations on high peaks or in deep valleys, proving the inadequacy of the free air reduction. As the latter residuals had a marked relation to the height of the station above or below the average elevation, in discussing the 1894 results a reduction term was introduced by me corresponding to the attraction of the topography above or of the deficiency of topography below the average plain for stations whose elevations were respectively greater or less than the average elevation, this average being taken within an arbitrarily assumed radius of 100 miles of the station. This procedure was equivalent to subtracting the attraction of the topography, as in the Bouguer reduction, and then adding as a compensation term the effect of a plate of average surface density, whose thickness is the average elevation of the surrounding region, as illustrated in the diagram.⁹ The result of this was to

⁸ In 1895 this was called the Faye reduction, on account of a suggestion in his papers, but it had not previously been applied. A similar reduction was independently used by Gilbert, termed by him a reduction to mean plain, and using the average elevation within 30 miles of the station.

⁹ The average elevation correction to reduce to sealevel was this:

$$dg = + \frac{2gH}{r} - \frac{2gH_1\delta}{r_4\Delta} + T + \frac{2gH_1\delta}{r_4\Delta}$$

$$= + \frac{2gH}{r} + T + \frac{2gh\delta}{r_4\Delta} \quad (\text{form used in 1895}).$$

where g is gravity at sealevel, H is elevation of station above sealevel, H_1 is average elevation above sealevel, h is $H_1 - H$, r is radius of the earth, δ is density of matter lying

eliminate the effects of over and under compensation developed by the free air method in mountainous regions. This method of applying the compensation as the negative attraction of a horizontal plate corresponded to the method then in use of computing the attraction of the topography. The results did not afford any proof of regional as against local compensation of topographic features, as was then thought from a comparison with the free air reduction results, for the reason that, as shown above, the latter do not correspond to a theory of complete local compensation.

As will be pointed out later, recent complete reductions by the Hayford method show almost no differences in results between local compensation and regional compensation to some limit less than 104 miles, so that the results, using an average elevation compensation, taking the average within 100 miles of the station, as was done in 1895, should be practically the same as with a complete local compensation.

This average elevation reduction was computed by me and published for 59 stations, about twenty-five years ago, and the resulting anomalies as computed and published at that time for the three methods above described are given in the following Table I, with also the anomalies for Hayford's method (1912). The results are given for 42 stations, these being all for which a direct comparison can be made from the originally published results.¹⁰

above sealevel, Δ is mean density of the earth, and T is a topographic correction due to departure of the surface from a plain (explained in Appendix No. 1, 1894, pp. 22, 23). In the second member of the first equation above, the first term is the correction for elevation, the second term for attraction of matter above sealevel, and the last term for compensation. The first three terms constitute the Bouguer reduction and the first and third the free air reduction. The treatment of ocean areas is explained in the same reference, page 26. The compensation term above represents the attraction, on a point on its surface or without it, of an indefinitely extended horizontal plate, and it therefore does not require any assumption as to the depth of compensation or its density or distribution, so long as it lies in homogeneous horizontal layers and its total amount is equivalent to the weight of a plate of the average surface density and having a thickness equal to the average elevation.

¹⁰ Coast and Geodetic Survey Report, 1894, App. No. 1, pp. 26, 28, 29; Report, 1897, App. No. 6, p. 309; Am. Journal of Science, vol. i, March, 1896, pp. 188, 191; Coast and Geodetic Survey Special Publication No. 10, pp. 76, 81, and No. 12, p. 24.

I. *Comparison of Anomalies in the Force of Gravity by old and new Reductions*
(Results as originally published)

Station.	Anomalies (in dynes), g observed, — g computed.				
	Elevation. Meters.	Bouguer reduction (no compensation). Dynes.	Free air reduction (compensation for station elevation). Dynes.	Average elevation re- duction (Putnam, 1895). Dynes.	New method (Hayford, 1912). Dynes.
For 25 stations in United States, observations in 1894 and 1895:					
Washington, D. C. (Smithsonian)....	10	+ .015	+ .016	+ .015	+ .037
Ithaca, New York.....	247	— .063	— .039	— .029	— .025
Charlottesville, Virginia.....	166	— .056	— .038	— .019	— .015
Deer Park, Maryland.....	770	— .053	+ .024	— .005	+ .008
Colorado Springs, Colorado.....	1,841	— .221	— .038	+ .003	— .009
Denver, Colorado.....	1,638	— .215	— .056	.000	— .018
Pikes Peak, Colorado.....	4,293	— .239	+ .226	+ .006	+ .019
Gunnison, Colorado.....	2,340	— .263	— .007	+ .035	+ .018
Grand Junction, Colorado.....	1,398	— .192	— .052	+ .033	+ .022
Green River, Utah.....	1,243	— .214	— .090	— .003	— .023
Grand Canyon, Wyoming.....	2,386	— .236	+ .016	— .010	— .004
Norris Basin, Wyoming.....	2,276	— .205	+ .030	+ .016	+ .019
Lower Geyser Basin, Wyoming.....	2,200	— .221	+ .006	— .001	— .003
Pleasant Valley, Utah.....	2,191	— .220	+ .002	— .013	+ .002
Salt Lake City, Utah.....	1,322	— .179	— .053	+ .002	+ .008
Austin, Texas (capitol).....	170	— .062	— .043	— .036	— .010
Austin, Texas (university).....	189	— .064	— .043	— .038	— .012
Laredo, Texas.....	129	— .065	— .052	— .051	— .022
Galveston, Texas.....	3	— .035	— .035	— .035	— .011
New Orleans, Louisiana.....	2	— .033	— .033	— .033	— .015
Calais, Maine.....	38	— .021	— .018	— .015	— .010
Cambridge, Massachusetts.....	14	— .009	— .008	— .003	+ .003
Boston, Massachusetts.....	22	— .007	— .005	— .001	+ .003
Princeton, New Jersey.....	64	— .038	— .032	— .032	— .021
Philadelphia, Pennsylvania.....	16	+ .004	+ .006	+ .011	+ .020
For 17 other stations:					
Yakutat Bay, Alaska.....	4	— .054	— .061 ¹¹	+ .019	— .034
Pyramid Harbor, Alaska.....	5	— .039	— .043	+ .067	+ .052
Juneau, Alaska.....	5	— .047	— .049	+ .038	+ .035
Sitka, Alaska.....	9	+ .005	+ .004	— .001	+ .006

¹¹ Free air anomalies for last group are derived from Coast and Geodetic Survey Special Publication No. 10, pp. 76 and 81, and No. 12, p. 24.

Station.	Anomalies (in dynes), <i>g</i> observed, — <i>g</i> computed.				
	Elevation.	Bouguer reduction (no compensation).	Free air reduction (compensation for station elevation).	Average elevation reduction (Putnam, 1895).	New method (Hayford, 1912).
	Meters.	Dynes.	Dynes.	Dynes.	Dynes.
Wrangell, Alaska.....	7	— .039	— .040	+ .014	+ .016
Burroughs Bay, Alaska.....	0	— .097	— .101	— .044	— .025
Port Simpson, British Columbia.....	6	— .019	— .017	+ .021	+ .021
Seattle, Washington (high school)....	74	— .135	— .137	— .079	— .095
San Francisco, California.....	114	— .017	— .030	— .047	— .025
Mount Hamilton, California.....	1,282	— .039	+ .091	— .030	— .005
Hoboken, New Jersey.....	11	+ .008	+ .006	+ .008	+ .022
Baltimore, Maryland.....	30	— .034	— .031	— .034	— .013
Saint Paul, Alaska ¹²	12	+ .033	+ .030	+ .026	— .002
Honolulu, Hawaii.....	6	+ .194	+ .190	— .010	+ .052
Mauna Kea, Hawaii.....	3,981	+ .244	+ .628	+ .068	+ .183
Saint Georges, Bermuda.....	2	+ .217	+ .212	— .037	+ .018
Jamestown, Saint Helena.....	10	+ .209	+ .211	— .045	+ .058
For all 42 stations, range.....		.507	.765	.147	.278
Mean, with regard to sign.....		— .060	+ .013	— .006	+ .005
Mean, regardless of sign.....		.104	.068	.025	.024
For first 25, United States stations, range..		.278	.316	.086	.062
Mean, with regard to sign.....		— .116	— .013	— .008	— .002
Mean, regardless of sign.....		.117	.039	.018	.014

A comparison of the average elevation anomalies with those by the Bouguer and free air reductions showed that the large anomalies by either of the latter were eliminated. This is particularly noticeable in comparing the anomalies for stations in mountainous regions, and with the free air anomalies for summit stations such as Pikes Peak, Deer Park, Mount Hamilton, and Mauna Kea, and stations below the general level, as Denver, Grand Junction, and Green River. This average elevation method of 1895 was the first that eliminated the excessive anomalies in mountainous regions and on islands. It was based on a theory of general compensation, and, as stated, the results confirmed the validity of the equilibrium, or isostatic, theory of the condition of the earth's crust.¹³ The

¹² A correction is applied to the 1895 residuals at Saint Paul to compare with the later observation used in 1912.

¹³ American Journal of Science, 1896, p. 192.

average elevation anomalies of 1895 show substantially as great an improvement over the two older methods, judged by the accordance and range of the anomalies, as do the Hayford anomalies of 1912.

Different constants were used in these two latter reductions, and, to obtain a more direct comparison between them, constant corrections are applied, $+.008$ to the 1895 anomalies and $+.002$ to the 1912 anomalies, to make the algebraic sum of the anomalies for the 25 United States stations zero for each group respectively. This is equivalent to the customary procedure of adding a constant term on the assumption that gravity in the United States, as determined by the stations considered, is normal. The results are given in Table II.

II. *Comparison of Anomalies in the Force of Gravity by the 1895 and the 1912 Reductions, Gravity normal in the United States*

Station.	Anomalies (in dynes), g observed, $-g$ computed.	
	Average elevation reduction (Putnam, 1895).	New method (Hayford, 1912).
	<i>Dynes.</i>	<i>Dynes.</i>
For 25 stations in United States, observations in 1894 and 1895:		
Washington, D. C. (Smithsonian).....	$+.023$	$+.039$
Ithaca, New York.....	$-.021$	$-.023$
Charlottesville, Virginia.....	$-.011$	$-.013$
Deer Park, Maryland.....	$+.003$	$+.010$
Colorado Springs, Colorado.....	$+.011$	$-.007$
Denver, Colorado.....	$+.008$	$-.016$
Pikes Peak, Colorado.....	$+.014$	$+.021$
Gunnison, Colorado.....	$+.043$	$+.020$
Grand Junction, Colorado.....	$+.041$	$+.024$
Green River, Utah.....	$+.005$	$-.021$
Grand Junction, Colorado.....	$-.002$	$-.002$
Norris Basin, Wyoming.....	$+.024$	$+.021$
Lower Geyser Basin, Wyoming.....	$+.007$	$-.001$
Pleasant Valley, Utah.....	$-.005$	$+.004$
Salt Lake City, Utah.....	$+.010$	$+.010$
Austin, Texas (capitol).....	$-.028$	$-.008$
Austin, Texas (university).....	$-.030$	$-.010$
Laredo, Texas.....	$-.043$	$-.020$
Galveston, Texas.....	$-.027$	$-.009$
New Orleans, Louisiana.....	$-.025$	$-.013$
Calais, Maine.....	$-.007$	$-.008$
Cambridge, Massachusetts.....	$+.005$	$+.005$
Boston, Massachusetts.....	$+.007$	$+.005$
Princeton, New Jersey.....	$-.024$	$-.019$
Philadelphia, Pennsylvania.....	$+.019$	$+.022$

Station.	Anomalies (in dynes), g observed, — g computed.	
	Average elevation reduction (Putnam, 1895). <i>Dynes.</i>	New method (Hayford, 1912). <i>Dynes.</i>
For 17 other stations:		
Yakutat Bay, Alaska.....	+.027	— .032
Pyramid Harbor, Alaska.....	+.075	+.054
Juneau, Alaska.....	+.046	+.037
Sitka, Alaska.....	+.007	+.008
Wrangell, Alaska.....	+.022	+.018
Burroughs Bay, Alaska.....	— .036	— .023
Port Simpson, British Columbia.....	+.029	+.023
Seattle, Washington (high school).....	— .071	— .093
San Francisco, California.....	— .039	— .023
Mount Hamilton, California.....	— .022	— .003
Hoboken, New Jersey.....	+.016	+.024
Baltimore, Maryland.....	— .026	— .011
Saint Paul, Alaska.....	+.034	.000
Honolulu, Hawaii.....	— .002	+.054
Mauna Kea, Hawaii.....	+.076	+.185
Saint Georges, Bermuda.....	— .029	+.020
Jamestown, Saint Helena.....	— .037	+.060
For 42 stations, range of anomalies.....	.147	.278
Mean, with regard to sign.....	+.002	+.007
Mean, regardless of sign.....	.025	.024
For 25 United States stations of 1894 and 1895,		
range	.086	.062
Mean, with regard to sign.....	.000	.000
Mean, regardless of sign.....	.018	.014

The above comparison shows that the average elevation reduction of 1895 gave nearly as good an accord of anomalies as the Hayford method of 1912, and also that the individual anomalies, with few exceptions, follow the same trend. In this comparison most weight should be given to the first group of 25 United States stations, and for these there is a small but appreciable advantage in the 1912 results.

As the superiority of the more recent method is admitted, it should be explained that this comparison is now made for two reasons: First, for historical completeness, as the work of 1895, very likely because of the way in which it was published, has been largely overlooked in the extensive comparisons which have been made of recent with older reduction methods, although the 1895 method was as definite as and more logical than those preceding and gave much more accordant results. Second, the fact is important in drawing deductions as to the validity of assumptions

because of the accordance of gravity anomalies, that so favorable results as to small anomalies were obtained with a method of reduction based on such generalizations as a compensation for the average elevation within 100 miles of the station, with both attraction and compensation computed as indefinitely extended horizontal plates and without any assumption as to the depth, thickness, or density arrangement of the compensation.¹⁴

COMPARISON OF RESULTS FOR REGIONAL OR LOCAL COMPENSATION

The evidence from the gravity determinations of the last half century is strong that a general condition of isostatic equilibrium exists in the outer portions of the earth's crust. The question of how close is this adjustment, of how local is the compensation of the topography, is of interest. If the compensation is quite complete for each small topographic feature, so that a single mountain or hill or canyon is exactly compensated by a less dense or a more dense material beneath, the outer portions of the earth would in detail be in a condition of nearly perfect equilibrium and would largely be free from stresses due to the supporting of topographic features. On the other hand, if the compensation is more general, such features of moderate extent would be supported by the partial rigidity of the earth's outer materials.

On my suggestion, in 1912 Hayford and Bowie made a study of this question by computing the anomalies for 45 stations, using regional instead of local compensation to three different zones whose outer radii were respectively about 12, 37, and 104 statute miles, and by comparing the anomalies thus obtained with those for complete local compensation, concluded that the evidence indicated that the assumption of complete local compensation is nearer the truth than regional compensation, even within the smallest of these three zones.¹⁵

In 1917 Bowie applied the same method to 124 stations in the United States, and compared the anomalies for stations grouped according to their location.¹⁶ The most significant of these are two groups in mountainous regions, one of 22 stations below the general level, the other of 18 stations above the general level. Regional compensation for the two smaller zones—that is, to the limit of 37 miles—gives average results practically identical with local compensation, and it is concluded that there is no evidence favoring regional or local compensation within this

¹⁴ These 1895 anomalies were also the result of a first trial only of the method then used without testing any variations in assumptions.

¹⁵ Coast and Geodetic Survey Special Publication No. 10, p. 98.

¹⁶ Coast and Geodetic Survey Special Publication No. 40, p. 85.

limit. By comparing the average anomalies for the outer zone, however, Bowie concludes that local compensation is much nearer the truth than is regional compensation to a distance of 104 miles.

From general considerations, this conclusion may not be improbable, but it should be noted that definite conclusions on this subject, based on the gravity residuals, are difficult because of the nature of the effects being measured. The pendulum measures the vertical component of the attractive and other forces which make up the so-called force of gravity. Hayford assumes the center of gravity of the compensation to be about 35 miles below the surface of the ground. The effect of a given compensation on gravity at a station will be nearly as great when the compensation is displaced a moderate distance horizontally as when it is directly underneath the station, and the compensation beneath a station will have an appreciable effect for a considerable distance surrounding it.

In a previous paper¹⁷ I suggested the desirability of testing this matter by comparing the anomalies from pairs of stations in the same general locality, but differing considerably in elevation, as in such a comparison distant effects and various uncertainties will be largely eliminated, and, furthermore, it is in such regions that incomplete compensation might be most likely to occur.

The following, Table III, gives the results for the pairs of stations for which comparable values are available.¹⁸

¹⁷ *Science*, December 20, 1912, p. 869. Barrell also developed later the same idea. *Journal of Geology*, 1914, p. 160.

¹⁸ The differences are taken from the results in *Coast and Geodetic Survey Special Publication No. 10*, p. 100, and *No. 40*, p. 91, for Cloudland—Hughes.

III. *Comparison of Differences in Anomalies for Pairs of Stations with local and regional Compensation (all computed by Hayford Method)*

Station.	Elevation.	Differ- ence in ele- vation.	Difference in anomaly (in dynes), sub- tracting lower from higher station.			
			Local compen- sation.	Regional compensation.		
				To 12 miles.	To 37 miles.	To 104 miles.
	Meters.	Meters.	Dynes.	Dynes.	Dynes.	Dynes.
Mauna Kea, Hawaii.....	3,981	3,975	+.131	+.118	+.105	+.068
Honolulu, Hawaii.....	6					
Gornergrat, Switzerland.....	3,016	2,597	+.046	+.041	+.023	+.016
Saint Maurice, Switzerland..	419					
Pikes Peak, Colorado.....	4,293	2,452	+.028	+.020	+.016	+.012
Colorado Springs, Colorado..	1,841					
Yavapai, Arizona.....	2,179	1,330	+.011	+.010	+.010	+.012
Grand Canyon, Arizona.....	849					
Mount Hamilton, California.	1,282	1,168	+.020	+.020	+.011	+.029
San Francisco, California...	114					
Cloudland, Tennessee.....	1,890	896	+.033	+.031	+.031	+.031
Hughes, Tennessee.....	994					
Means for 6 pairs.....			+.045	+.040	+.033	+.028
Means for 4 pairs in United States.....			+.023	+.020	+.017	+.021

The mean differences of anomaly show greater accordance for regional compensation to 104 miles than for local compensation. The number of pairs is too small, however, to more than indicate that this method should also be considered in studying the question of regional compensation.

It is of interest that these differences are all positive, as I previously pointed out.¹⁹ Bowie has studied this effect in the anomaly results on comparing adjacent stations of materially different elevation.²⁰ His suggested explanations do not appear to make these results the less useful in considering the question of regional compensation. The effects mentioned would affect the groups of stations in much the same manner that they do the results from the pairs. For 14 pairs of stations an average difference of +.013 dyne is found, all the results but one being positive. There is here fairly strong evidence of a systematic variation in the gravity anomalies of about this amount as between stations so located. This indicates the possibility of the existence of systematic effects in the reductions not yet definitely located.

¹⁹ Science, December 20, 1912, p. 869.

²⁰ Coast and Geodetic Survey Special Publication No. 40, p. 93.

Among the great unsolved physical problems of the earth's crust are the causes of the subsidence and uplifting of large areas, the overthrust and folding of strata, and the formation of mountain ranges. Although the results of these actions are so openly and impressively displayed in our western mountain regions, the great and long acting forces which accomplished and are still continuing this work are still a subject of discussion with divergent views. Isostasy acts to bring about equilibrium where there is lack of adjustment, and, even without the observational data available, this theory would be a fairly obvious conclusion from evidence, within the experience of man, as to the strength of materials and the flow of solids under pressure. The forces which have during ages caused continental areas to oscillate up and down through many thousands of feet and have folded and thrust over rock strata of great thickness appear to be so far removed from comparisons within human experience as to make a conclusive explanation difficult.

SOME CONSIDERATIONS TOUCHING ON ISOSTASY *

BY H. O. WOOD ¹*(Presented by title before the Society December 29, 1922)*

CONTENTS

	Page
Isostasy in geology.....	303
Geodetic establishment of isostatic equilibrium.....	304
Implications of complete isostasy.....	304
Difficulties of geologic interpretation.....	306
Purpose of present discussion.....	307
Superior strength of surface shell in horizontal direction.....	307
Spherical continuity of surface shell confining yielding layer.....	309
Widespread elastic strain spherically distributed, local failure.....	310
Effects of the growth of batholiths.....	312
Localized modification of strength in surface shell.....	313
Deformation during the erosion-deposition cycle.....	313
Seismologic indications of a weak shell.....	313
Summary of conclusions.....	314
References.....	315

ISOSTASY IN GEOLOGY

Since Dutton's exposition of the principle of isostasy, in 1889, the advance of geologic knowledge has made more and more probable, in a general sense, the reality of isostatic adjustment in the earth. Nevertheless there has been, and yet is, considerable diversity of opinion among geologists regarding the degree of its completeness, the depth at which it is effective, and the mechanisms involved in its accomplishment. Recent discussions by Barrell,¹ Leith,² and Willis³ may serve to illustrate this. Moreover, so far as the present writer is aware, no one (except himself,⁴ and he only partially and tentatively) has invoked the principle, on strictly geologic grounds, to explain relations existing among crustal

* Manuscript received by the Secretary of the Society December 19, 1921.

This paper is one of a series composing a symposium on isostasy.

¹ Introduced by William Bowie.

units of small area, or conditions affecting such units. And earlier opinion was distinctly adverse to this.

GEODETIC ESTABLISHMENT OF ISOSTATIC EQUILIBRIUM

On the other hand, recent geodetic work, especially that conducted by Hayford⁵ and Bowie,⁶ of the United States Coast and Geodetic Survey, and following them by Burrard⁷ and his colleagues, of the Trigonometrical Survey of India, has gone far toward establishing it as a reality, by a preliminary treatment and least-square adjustment of considerable bodies of refined physical measurements, that the outer shell of the earth above a depth of about 100 kilometers departs only very slightly from a condition of flotation equilibrium among its parts. Even when prisms of the shell of small area are dealt with, the excess or defect of mass found in this way is small, while for prisms of large area the excess or defect of mass thus found is practically negligible—less than two-tenths of 1 per cent of the mass of the prism for the United States. So complete and so intimate an adjustment is thus indicated that Hayford ventured to predict that “future investigations will show that the maximum horizontal extent which a topographic feature (that is, an excess or defect of mass in a prism—Wood) may have and still escape compensation is between one square mile and one square degree.”

As stated above, it can not be said that geologists in general have been led by geologic evidence to expect so intimate and so completely effective isostatic adjustment. Objections to it have been pointed out. Even if Hayford's limiting estimates of area were to be increased considerably, these objections would hardly be met thereby.

IMPLICATIONS OF COMPLETE ISOSTASY

Questions have been raised as to the assumptions made and the treatment and mathematical adjustment employed by the geodesists in discussing their admittedly precise physical measurements. Consequently their conclusions have been questioned. This is not a matter for geologists, as such, to discuss. At present the objections which have been raised do not seem to be sustained. And, if the assumptions and methods are valid, there can be little doubt that geodesists have established the fact of isostatic adjustment, certainly over large regions of the earth at the present time.

The geodetic findings imply—nay, require—that the earth shell above the level of isostatic equilibrium must be very weak—at any rate, *in offering resistance to stresses exerted in the vertical direction* (the pres-

ent writer will return to this point); otherwise excesses or defects of mass in prisms of considerable area could be upheld or held down by the material strength of the shell when it is supported, as it is, upon a *contained* spherical continuum of subjacent matter (whatever the condition of this), just as it can, and does, support small loads over small areas and, perhaps, large loads over very small areas. But, on the other hand, in geology there are many observed facts which indicate that the earth's outer shell is very strong, especially in its upper portion—at least in *sustaining, transmitting, or in offering resistance to stresses exerted in the horizontal direction*. Many of the effects observed and ascribed to horizontal stresses are on the grand scale, and the intimate responses expectable in weak materials do not seem often to occur.

Is there need here to recite the observed facts of mountain folding, overthrusting (or underdragging), and other such evidences of horizontal shortening and reduction of area presented in so many places on the regional if not on the world-wide scale? While we must, of course, scrutinize from time to time the explanations of this action in respect to mechanisms and details, is there anything known at present to indicate any adequate explanation of the grander dynamical phenomena except horizontal compression in fairly competent materials, despite the objections to this so far raised? If so, the present writer is not aware of it. And any modifications of opinion in regard to details which seem now to deserve consideration still appear to require an outer shell strong with respect to forces exerted horizontally. Moreover, the probability of this property of great strength in the shell is sustained by appeal to certain physical facts, like the effects found when great pressures are applied to rock substances confined in strong, rigid containers, as in the experiments conducted by Adams⁸ and others. Here, however, *the factor of time*—that quantity so abundantly available in geologic happenings—is neglected. And the importance of the factor of time is very great.

Moreover, to confuse us, there are also observed geologic facts which indicate that the outer shell is weak (perhaps, however, weak especially in respect to stresses productive of motion in the vertical direction, as Leith has so clearly pointed out). And, again, appeal may be made to certain physical principles and experiments to support this, as Hayford⁹ indicated so emphatically a few years ago. To illustrate, mention may be made of the slow, progressive, permanent yielding (whatever its nature) which some substances ordinarily rigid undergo under enduring stresses near to their elastic limit (even in some instances well below their elastic limit for so-called instantaneous forces), of the predominance of

the factor of time in this behavior, and of the acceleration of such yielding under moderately elevated temperatures.

Thus the geologist, though convinced that the outermost shell of the earth is very strong in respect to certain conditions of stress, finds his own observations confusing in some ways, as well as the facts and principles of physics to which he must appeal. He has few measurements—perhaps none—which approach in precision those utilized in the geodetic discussion. From a standpoint of debate he occupies a weak position in putting forward an opinion or, better, a judgment supported by qualitative and in some respects mutually contradictory observations in opposition to a judgment reposing on sound measurements treated in a probably legitimate way. Fortunately, mere debate has no place in scientific inquiry.

DIFFICULTIES OF GEOLOGIC INTERPRETATION

A figure of speech may here serve a useful purpose. In the chronicle of the earth geodesists have read off—may we say glibly?—a single sentence or phrase *recently written and undefaced*, while geologists must patiently decipher innumerable fragmentary letters, words, and phrases found here and there in the tattered pages of a book of encyclopedic dimensions scarcely a line of which has escaped mutilation. By far the greater part of this book has been destroyed during the writing of it, and of what remains only a small portion has been deciphered and interpreted, some of it erroneously, without doubt. Nevertheless, since no one geologist can personally examine more than a very small fraction of the fragmentary remains, he *must* accept, for the rest, the readings of his colleagues. Small wonder that there is a diversity of interpretation and opinion; that even a single worker may happen upon phrases which seem to stand in conflict. Notwithstanding all this, there has come to be a consensus of opinion in many matters that have seemed clear and consistent which would appear to become uncertain and of doubtful consistency if they must be brought into strict accord with the meaning expressed in the single undefaced phrase pointed to by geodesists. The geologist is thus in something of a dilemma. Must he review and reconstruct his whole philosophy of earth dynamics, or, to shift the figure, is it possible that the geodesist, in pursuing a straight and level short cut to his destination, has missed a good part of the scenery? Granting the geodetic facts, must these be accepted and interpreted narrowly, or are there alternative ways to utilize them? About all this whole books must yet be written. It is not easy to select a few clear, vital principles to illumine a brief discussion; but it is sure, nevertheless, that geologists

must *endeavor* to reconcile, so far as possible, the interpretation of their multitudinous and somewhat vague observations with that of the few but precise data of geodesy.

PURPOSE OF PRESENT DISCUSSION

No new measurements are here brought forward, no detailed analyses. None of the matters to be discussed are new. They have even received emphasis heretofore. But numerous conversations and informal discussions have led the writer to believe that they may merit coherent assembly and fresh emphasis.

SUPERIOR STRENGTH OF SURFACE SHELL IN HORIZONTAL DIRECTION

First, then, it appears reasonable that within a certain range of depth there may be a more or less regular shell which will sustain, transmit, or resist additional applied stress more effectively in the horizontal than in the vertical direction. Barrell and others have touched upon this, but it does not seem to have been fully developed anywhere. The actual earth, of course, is lacking in homogeneity, but for the moment we must neglect this. There seems to be general agreement that at some depth, under the pressure of superincumbent matter alone (but especially if this is combined with an elevated temperature), rock matter will yield readily in the direction of any open space or any region of accommodation. Willis has given a convincing analysis of this. There are some who think that this depth is very irregular, so that it is very different in different regions. Others think that it is fairly definite and reasonably uniform, when the actual slight inhomogeneity of the material is taken account of.

At the surface most rock substances are rigid and elastic, capable of sustaining, without any permanent deformation, considerable stresses enduring for considerable intervals. Then let it be granted, or assumed, that at some depth (in the actual earth different in different places, either slightly or greatly, as the case may be) the rock matter will just begin to yield under the pressure of the overlying material if any mode of accommodation whatever is afforded. Then, somewhat above this depth, it will not, under ordinary circumstances, yield. Let us now consider a slender column of rock substance extending upward to the surface from this depth, at which it will almost, but not quite, yield. This column is *confined* by the surrounding rock substance and can not expand laterally; yet each unit of it bears the load of all superincumbent units and would, if not so confined, expand laterally to a certain extent; but, above the depth of incipient potential yielding, its lateral expansion would not equal

in volume its vertical reduction of volume by compression; and this lateral expansion would take place in all directions in the plane perpendicular to the vertical.

The difference between the horizontal and the vertical effects is given, in elastic substances, by Poisson's ratio, and this varies for most substances between 0.2 and 0.3. In seismologic computations the value for

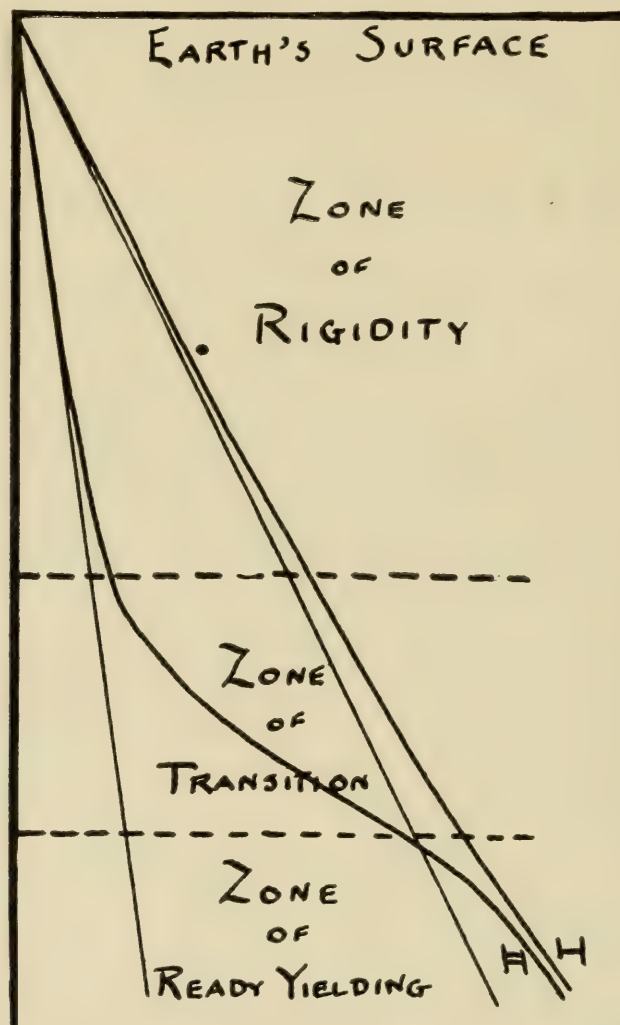


FIGURE 1.—Diagram to illustrate Growth of Stresses with Depth

- I. Increase with depth of vertical stress from load.
- II. Increase with depth of lateral stress from load.

the earth's outer shell has been taken at 0.27. Consequently, above the region of incipient potential yielding, the overlying load produces a certain lateral stress which is considerably less than the vertical stress from the same cause, while below, in the region of ready potential yielding, the lateral stress from load should be approximately equal to the vertical stress, and the conditions may be considered approximately hydrostatic

for a steady configuration. This postulates nothing as to the mechanism of yielding. In the intervening shell there is thought to be a comparatively rapid growth of the lateral stress with depth. Nothing is here said as to quantities. But the *form* of the curve of lateral stress as it increases with depth, compared with the curve of vertical stress, which increases uniformly with depth as the load increases, may be illustrated by the diagram, figure 1. No meaning is here attached to the *scale* of this diagram. Moreover, this is not a complete picture of the conditions, for it does not take into account the intimate tethering of particles in an elastic medium more completely than this is cared for by Poisson's ratio; but this picture will serve to bring out the writer's point, that a given stress which, applied vertically at a given depth, would just produce potential yielding, would, if applied horizontally at the same point, simply add to the stress from load, leaving the whole bearable. Thus the outermost shell down to a certain depth may sustain, resist, or transmit toward regions of weakness horizontal—that is, tangential—stresses which, applied vertically, would produce isostatic adjustment. It may be that this point will help to clarify the uncertain status of opinion regarding the strength of the earth's crust.

SPHERICAL CONTINUITY OF SURFACE SHELL CONFINING YIELDING LAYER

A second point—a very obvious one—that the present writer would lay stress upon is that every earth prism, down to the level of incipient yielding, is *contained* and constrained by those which surround it, *except at its surface*, probably more effectively than any like control in laboratory experimentation. Though we know it well, we must not forget, even momentarily, that the earth is a globe, and this outermost fairly rigid layer of it a *continuous* spherical shell. Therefore it is hardly legitimate, especially in thinking of the isostatic problem, where the whole earth is necessarily involved, to consider elements of the shell as plane slabs with free boundaries, or with hypothetical abutments of absolutely rigid matter which may be supposed to apply stresses from without upon the edges of the slab. Nor should these elements be thought of as flat domes unsupported beneath, with free boundaries, or hypothetical abutments like those specified for the slab. For example, there is no doubt that such domes, if unsupported below or at the sides, would slump down under their own weight, even when of small area; and either domes or slabs might, if standing alone, break or shear, and thus fail to sustain or transmit horizontal stress imposed from without. But it seems not to be a necessary consequence that elements of a continuous spherical shell of the

earth, resting upon and confining the potentially yielding matter beneath, and everywhere affected equally by the centrally directed gravity field of the earth, must slump or crush or otherwise fail to sustain and transmit horizontal—that is, tangential—stress, until this has become so great as to bring about failure localized in the weakest elements. When there is deformation of one or more elements, this must, of necessity, involve some change of configuration, molecular if not molar, elsewhere in the outermost shell, with compensatory readjustments in the subjacent layer capable of ready yielding; for there are no void spaces worth mentioning in the potentially yielding region, and any other means of accommodation of augmented downward pressure in one region means either uplift elsewhere or further increase in the hydrostatic pressure tending to compact the subjacent material (unless there is storage of energy with endothermic reactions). If a mountain mass or a continent sinks because it is too heavy to float at the level it has attained, something else must rise or there must be changes of conditions in the depths.

So, if the earth's radius undergoes shortening throughout a given interval, whatever the cause of this (loss of heat, progressive gravitational compacting, crystallization, or reduction of volume with endothermic changes), the peripheral shell must decrease in area. This requires either uniform thickening, or regional distortion and wrinkling, or both thickening and distortion together in some combination. Of these possibilities wrinkling is positively observed, though it is not positively proved to be due to this cause. To produce wrinkling *under these circumstances*, tangential stresses must in some way bring about translation of material toward the wrinkling areas, which will be, at any particular epoch, the weak prisms of the outermost shell.

WIDESPREAD ELASTIC STRAIN SPHERICALLY DISTRIBUTED, LOCAL FAILURE

It is a hypothesis with the writer that accumulating *elastic* strain in the shell above the depth of incipient yielding, oriented tangentially under the earth's gravity field which keeps the elements of the surface shell in approximate isostatic equilibrium, may ultimately find relief over a very wide region of the globe in the gradual failing of some relatively small region of weakness where unfolding takes place and consequent reduction of geographic area occurs. But if isostasy is to be maintained approximately at all times, this action must be accompanied both by adjustment and counter-transfer of matter in the layer of yielding, and by reduction of density in the columns affected by the unfolding, since these can not increase significantly in mass without disturbing isostatic balance.

Such action need not be complete. Indeed, some excess of mass is found in some elevated areas.

Of course, if it be granted that significant local variation in the depth of flotation equilibrium is possible, then no such adjustments or density changes need be hypothesized, for the compressed prisms could then float for a time, possibly a long time, *lower* as well as higher than before their compression.

But it is to be noted that the action above hypothesized need not violate the principle of isostasy in any significant degree; for with the upfolding there would be incipient arching, incipient relief of pressure beneath the arching area, incipient expansion, and possibly even incipient melting from relief of pressure. These tendencies would go hand in hand simultaneously at all stages of the process of relief of widespread strain by localized deformation. And the tendency to expansion beneath the folding region would be augmented by the heat generated mechanically in the process of deformation, and by the upward movement of the isogeotherms beneath the upwarping area. Thus might come about the necessary decrease in the average density of the columns whose surface parts had been elevated under the operation of tangential pressure supplied by widespread elastic strain.

To discuss all this thoroughly, and present a complete hypothetical picture of it, alone would require a book. All that is possible here is a mere outline of the idea that lateral strength combined with vertical weakness in a surficial spherical shell reposing upon, confining, and *loading isostatically* a globular interior the outer part of which may yield and conform, under excess pressure, to movements or changes of shape in the shell may make it possible to harmonize and adjust differences in opinion concerning the interpretation of patent geologic and geodetic findings.

Here favorable reference must be made to much of what T. Mellard Reade¹⁰ wrote concerning the origin of mountains, though without acceptance here of his primary thesis. In past and present mountain regions many batholiths have melted, risen, cooled and crystallized with accompanying volume and density changes; and, as Reade pointed out, and this is thoroughly consistent with the operation of the principle of isostasy, the only direction for relief of the stresses induced by such changes is the vertical. These changes appear to the writer to be consistent and expectable concomitants of incipient relief by incipient arching as the result of tangential pressure and the train of consequences of this. It seems also to the writer that such a combination of tangential pressure with vertical expansion and upward movement, surely involving

shearing as well as flow and fracture, accords well with Leith's observations and interpretations of rock cleavage.

EFFECTS OF THE GROWTH OF BATHOLITHS

However, it must also be pointed out that the observed occurrence of batholiths suggests a proximate cause and mechanism which may be appealed to quite independently of tangential pressure, as well as concomitantly with it, in explaining mountain building in harmony with isostatic adjustment. But in this case the cause of batholithic melting must be sought.

LOCALIZED MODIFICATION OF STRENGTH IN SURFACE SHELL

We come now, thirdly, to a consideration of the weak prisms in the outer envelope, where yielding under accumulating tangential stress may begin and go on, accompanied by subterranean density changes, until a mountain system has been built and the strain in the surface shell temporarily relieved. It is the overwhelming testimony of geology that the places of weakness which subsequently are folded up into mountains are the great synclinal troughs in which sedimentary material has been deposited until series often many thousands of feet in thickness have been accumulated. These light, unconsolidated, and uncemented materials thus come to form the upper part of earth prisms in places where earlier in the cycle there was stronger, denser rock, cooled by the blanket of water above it, which later subsided under the accumulating load into regions of higher temperature. These prisms are thus weakened in their upper, more competent portions.

So, if we start with a mountain region adjoining the sea, the ordinary action of erosion will remove what may be relatively weak matter from the mountain upland and deposit it, as a still weaker aggregate, in the adjoining trough of the sea. If we then grant that the outer shell can not sustain much change of stress in the vertical direction, a partially compensatory uplift of the mountain block and subsidence of the sea trough will ensue; and this will go on, strengthening the column of denudation by bringing up stronger rock to replace the weaker rock worn away and weakening the column of deposition in the manner already indicated, until baseleveling has advanced very far or gone to completion. This action demands a readjustment of matter in the yielding layer beneath the region affected which may be visualized as a slow shifting of matter from under the loaded region to beneath the unloaded region. I purposely avoid here the word undertow on account of a connotation of

streaming which this has come to carry to some students. Thus changes in the average relative densities of the two parts of the region of activity are brought about. The mountain column will not rise quite so much as it is lowered by denudation during a given interval, because relatively heavy matter moves in beneath it in establishing readjustment; and the sea column will not sink quite so much as it is upbuilt, because the addition of a comparatively thick layer of unconsolidated, and therefore light, sedimentary matter causes the column to press out from under it a relatively thin layer of heavy yielding matter; and there will be *lag* in this process of readjustment at every stage. The mountains will not rise nor the sea-floor sink so fast nor so far as they would if the process encountered less resistance of a viscous nature.

DEFORMATION DURING THE EROSION-DEPOSITION CYCLE

The process by itself will necessarily involve deformation. There will be subcrustal tractions; shearing stresses will be set up; there will be modifications of shape of rock bodies forming members of one or both columns; and there will be changes in the temperatures to which particular bodies are subjected. Locally, these may be manifested more importantly than the chief factors in the process. Again, a reasonably adequate picture of the whole process of transfer and readjustment would require a book, if indeed any such picture can yet be drawn; but, again, on the whole the movements near the surface would seem to involve largely shearing along sensibly vertical planes which Leith has emphasized as a fact of observation. What it is desired to emphasize here is, that the ordinary conception of denudation and deposition in adjacent areas, combined with reasonably complete subterranean transfers and readjustments in obedience to the isostatic principle at all stages, will develop weak prisms where earlier there were strong ones, and that ultimately these weakened prisms may gradually yield under accumulating tangential elastic stress, as discussed above.

SEISMOLOGIC INDICATIONS OF A WEAK SHELL

One other matter deserves attention here. In many respects it is the most important topic touched upon in this discussion; but an adequate and critical treatment of it would require greater space than the whole of the present discussion, and such a treatment is better undertaken by another. It deals with observations of greater precision, from the physicist's point of view, than any ordinary geologic work. It is this: The evidence of seismometry in several independent ways suggests that the material in

the earth at a depth of 30 to 50 kilometers is in a different condition from that outside this depth. For example, on the basis of the length of the seismic waves which are propagated over the surface, commonly about 63 kilometers, Wiechert deduced a depth of 31.5 kilometers for the "magmaschicht," which, as Galitzin¹¹ points out, agrees well with the depth of the melting temperature on the basis of an increase of 1 degree centigrade for each 36.7 meters of depth. Moreover, in one late study it has been inferred that the matter immediately below a depth of about 50 kilometers is in an expanded (and possibly molten) state, so that its density is appreciably less than that of the immediately overlying material. This study has not yet been published, so far as the writer is aware, but it is based on observations in Samoa in connection with the arrival times and characteristics, under known different conditions, of two differentiated parts of the earliest or longitudinal waves registered by seismographs. It is to be hoped that Angenheister will set this forth in the detailed and critical form it deserves.

It seems also that the *prime motion* in such displacements as those detected by survey in connection with earthquakes, as in California in 1906, and in other instances, and the progressive northward shifting of the International Latitude Observatory at Ukiah, California, recently discerned and pointed out by Lawson,¹² finds its best explanation in the *drag* of the overlying matter by a positive transfer of material in a subjacent layer of ready yielding.

These seismologic and similar findings, though as yet interpretations of comparatively meager data, if sustained by further work will greatly strengthen the geodetic argument for isostasy.

SUMMARY OF CONCLUSIONS

In conclusion, it is to be noted that vague terms, like *yielding* and *earth's outer shell*, have been employed consistently in preference to more specific or precise designations, such as plastic, viscous, fluid, etcetera, or set, flow, shearing, recrystallization, etcetera, and crust or asthenosphere, in order to avoid any misconceptions arising out of the definitions of these terms, or their employment, in connection with more specific hypotheses.

For the same reason no estimates of the depths of incipient or of ready yielding have been given above. However, by implication the depth of incipient yielding would be taken less than 30 kilometers on the basis of the seismologic data, and of Willis's estimate of 40 miles as the depth of the yield-point, taking no account of temperature increase downward.

It has been attempted here to combine into a coherent whole true tend-

encies, most of which obviously are every-day knowledge in physics and geology. To summarize: Combination of (1) the greater competence of rock, down to a certain depth, in the horizontal direction than in the vertical direction, (2) the spherical form of the earth assuring the continuity of the competent part of the outer shell and the confined status of the more freely yielding subjacent material, and (3) the weakening and strengthening of adjacent elements of the outer shell by readjustments brought about by erosion and deposition under effective isostatic control, may permit tangential elastic stresses to be generated, sustained, and transmitted to weak regions, so as to build mountains under effective isostatic control, so long as any effective compacting of the interior of the earth continues from any cause. Still, just as formerly, it is to a shrinking interior of the earth that geology looks for the prime mover by which its grander dynamical phenomena are brought about.

The moral of this discussion is that it appears possible to bring conceptions of the extreme isostasists and the most conservative students of earth dynamics into much closer harmony without doing violence to the fundamental views of either group. Nevertheless it is clear that certain of the dynamical concepts appealed to in geology are in need of fresh and critical scrutiny in the light of physics and the properties of materials.

REFERENCES

1. The strength of the earth's crust. *Journal of Geology*, volume XXII, numbers 1-8, 1914; *Journal of Geology*, volume XXIII, numbers 1, 5, and 6, 1915.
2. The structural failure of the lithosphere. *Science*, new series, volume LIII, March 4, 1921, page 1366.
3. Discoidal structure of the lithosphere. *Bulletin of the Geological Society of America*, volume 31, 1920, pages 247-302.
4. On a possible causal mechanism for heave-fault slipping in the California Coast Range region. *Bulletin of the Seismological Society of America*, volume 4, December, 1915.
5. The effect of topography and isostatic compensation upon the intensity of gravity. *United States Coast and Geodetic Survey Special Publication* number 10, 1912.
6. Investigations of gravity and isostasy. *United States Coast and Geodetic Survey Special Publication* number 40, 1917. Our present knowledge of isostasy from geodetic evidence. *Journal of Geology*, volume 25, 1917, page 422.
7. Investigations of isostasy in Himalayan and neighboring regions. *Trigonometrical Survey of India*, Professional Paper number 17, 1918. A brief review of the evidence on which the theory of isostasy has been based. *Geographical Journal* (London), volume 56, 1920, page 47.

8. On the amount of internal friction developed in rocks. *Journal of Geology*, volume XXV, 1917, pages 597-637, and earlier studies.
9. The relation of isostasy to geodesy, geophysics, and geology. *Science*, volume 56, 1911, page 199.
10. The evolution of earth structure, with a theory of geomorphic changes (especially Book II). London, New York, and Bombay, 1903.
11. *Vorlesungen über Seismometrie*. German translation edited by O. Hecker, page 149.
12. The mobility of the Coast Ranges of California, an exploitation of the elastic rebound theory. University of California publications, *Bulletin of the Department of Geology*, volume 7, 1921, page 431.

ISOSTASY AND EARTH MOVEMENTS¹

BY HARRY FIELDING REID

(*Read before the Society December 29, 1921*)²

CONTENTS

	Page
Introduction.....	317
Evidences of isostatic equilibrium.....	318
Objections to former isostatic equilibrium.....	319
Vertical uplift of mountain ranges.....	319
Relation of isostasy to folding and uplift.....	323
Isostasy and peneplanation.....	324
Isostasy and the rigidity of rock.....	324
Conclusion.....	326

INTRODUCTION

Geologists often ask too much of the principle of isostasy. When they find that isostasy will not explain all earth movements, they think it is not a true principle. Many of the most important earth movements are not due to an attempt to reestablish a disturbed isostatic equilibrium. James Hall made a splendid contribution to our knowledge of the geologic history of mountain ranges in 1859.³ He showed that the sediments of the Appalachian Mountains were laid down in a sinking syncline, and he inferred that the sinking was due to the weight of the sediments. While this weight must have contributed to the sinking, it is clear that great depressions have taken place without the addition of material; for many of the great deeps of the ocean, and as a particular example, the Tonga Deep, are so situated that they could never have received any large amount of sediments; and the elevation of mountain ranges after the accumulation of sediments could not be due to a reestablishment of isostatic

¹ Manuscript received by the Secretary of the Society December 22, 1922.

This paper is one of a series composing a symposium on isostasy.

² The main part of the evidence for the uplift of mountains by vertical forces, given in this article, was presented to the Geological Society at the Chicago meeting, in 1920. See this Bulletin, vol. 32, p. 33.

³ Natural History of New York, part vi, Paleontology, vol. iii, pp. 50-85.

equilibrium. There is some other cause, which we do not know, that produces these great movements.

But the principle of isostasy is of great value. It bears some analogy to the principle of the conservation of energy in the physical sciences. It does not always tell us what earth movements will take place, but it tells us that these movements must be of such a character that the amount of matter underlying a given area of the earth's surface is never materially increased or decreased; and if there be a transfer of matter at the surface by erosion and deposition, by folding of the strata or by any other means, then there must be a corresponding subterranean transfer in the opposite direction.

Isostasy could not be proved by geologic observations, although they might suggest it. Its proof is a geodetic proof, depending entirely on the deflection of the vertical and the anomalies of gravity, for it is only by such determinations that the masses underlying different regions can be compared.

EVIDENCES OF ISOSTATIC EQUILIBRIUM

The existence of isostatic equilibrium over the area of the United States has been proved by the determinations of Hayford and Bowie.⁴ These observations were made in regions of erosion and regions of deposition, at high and low altitudes, near the coast and in the interior, in regions where earth movements are active and in regions that have long been stable. The conclusions have been corroborated by the work of the Great Trigonometrical Survey of India, with one station at an altitude of 15,427 feet, in Tibet.⁵ The principle has also been applied to stations situated on islands, and to a number of stations in Europe, some in the Alps, and with satisfactory results. Nansen swung a pendulum on the ice, and in the *Fram*, over the Arctic Ocean, and found gravity normal.⁶ Hecker made determinations over the Atlantic, the Pacific, and the Indian oceans, and found only small deviations from the normal in the force of gravity.⁷ We are therefore forced to the conclusion that, at the

⁴ John F. Hayford: The figure of the earth and isostasy. U. S. Coast and Geodetic Survey, Washington, 1909. Supplementary investigation of the figure of the earth and isostasy. Same, 1910.

John F. Hayford and William Bowie: The effect of topography and isostatic compensation upon the intensity of gravity. Special Publication No. 10. Same, 1912.

William Bowie: Second paper. Special Publication No. 12. Same, 1912. Investigations of gravity and isostasy. Special Publication No. 40. Same, 1917.

⁵ Col. Sir Sidney Burrard: A brief review of the evidence upon which the theory of isostasy has been based. Geog. Jour., 1920, vol. lvi, pp. 47-59.

⁶ The Norwegian North Polar Expedition of 1893-1896, vol. ii, pt. viii. Pendulum observations by O. E. Schiøtz.

⁷ Veröff. d. Kön. Preuss. Geodätischen Institutes, Nos. 11 (1903), 16 (1908), 20 (1910).

present time, the world is everywhere in a fair degree of isostatic equilibrium. And, when we consider that this equilibrium holds in regions of active erosion and in regions of active deposition, the conclusion is inevitable that as the equilibrium is disturbed it is readjusted by subterranean flow, and that the earth is sufficiently yielding to permit this flow.

OBJECTIONS TO FORMER ISOSTATIC EQUILIBRIUM

If the earth does yield in this way, it follows that the earth has always been in isostatic equilibrium. Some geologists will not admit this; they contend that we are now in a period of mountain-building and of great disturbance, which permit the adjustment, but that this was not true in former geologic times. So far as I know, the objection is based on the contradiction to two hypotheses and not on the opposition to facts. The hypotheses are: (1) that mountains have been raised by the compression of the strata, and thus extra matter has been squeezed into them, and (2) that the earth is too rigid to yield to forces developed by the transfer of surface material.

VERTICAL UPLIFT OF MOUNTAIN RANGES

The study of the folds and faults and other characteristics of mountains led the geologists of the last century to replace the earlier ideas of von Buch, that mountains were suddenly uplifted by volcanic forces, with the idea that mountains were squeezed up by tangential pressure. It can be shown, however, from purely geological observations that many of the most important mountain ranges of the world owe their elevation, not to lateral compression, but to vertical uplift.

The Sierras of California suffered strong compression and close folding in pre-Cretaceous times. After this they were reduced to a peneplain which could not have been very much above sealevel, and in quite recent times they have been elevated, leaving the peneplain as a gentle slope to the west, but without any additional folding. On the east the mountains are bounded by a great and steep normal fault. It is evident that normal faults can not be formed by pressure alone, and I have shown^s that steep faults, normal or reverse, require the action of vertical forces. It is clear that the present elevation of the Sierras is not due to compression, but is due to vertical force acting long after the folding occurred.

The history of the Appalachian and the Rocky Mountains is very much like that of the Sierras. The Appalachians were strongly folded and faulted at the end of the Carboniferous. In the Cretaceous they had been

^s In a paper on the dynamics of faulting, soon to be published.

reduced to a peneplain, and in the Tertiary they were raised into a broad, low arch, and were carved by erosion to their present topography. A simple consideration of the strength of rock shows that such an arch, tens of miles in span, could not be supported by its ends, and therefore could not have been raised by simple tangential pressure against its ends, but must have been raised by vertical forces. The Rocky Mountains were reduced to a peneplain after the Cretaceous revolution. The distance from the sea makes it probable that this peneplain was originally a few thousand feet above sealevel; but its present elevation is eight to nine thousand feet, an elevation evidently due to vertical forces. The great monocline and the steep faults limiting the range along the Colorado front show the action of vertical forces.

The Andes were elevated long after the strata were folded. The major folding was apparently pre-Cretaceous; although some folding occurred later, it was not important. From early Tertiary time until well into the Pliocene the area stood at only moderate altitudes and suffered a general baseleveling. Transgressions of the sea occurred in several parts of South America in Eocene times and reached the flanks of the Andes in Peru. Transgressions also occurred in Lower and Middle Miocene times. The Lower Miocene flora on parts of the coast of Peru is identical with that of the Amazon basin, indicating free communication between the regions, with no intervening mountains more than about 6,000 feet high. There may have been some elevation in the later Miocene, but fossil Pliocene floras found at altitudes of 11,500 to 13,500 feet, and which could not have flourished at greater altitudes than 5,000 to 6,000 feet, show moderate altitudes in that period. The late Tertiary peneplain, standing now at an altitude of about 15,000 feet, must have been brought to maturity at not more than a few thousand feet above sealevel. The very slight difference between the present fauna and flora of the humid tropical western coast of Peru and the Amazon basin shows that an effective barrier has existed between these regions for only a short time, geologically speaking. There is a great scarp, still 4,000 feet high, in eastern Peru which marks a normal fault limiting the range, and enormous quantities of Pliocene and Pleistocene detritus cover both flanks of the eastern Andes in Bolivia.

All the facts prove that the elevation of the chain has been very recent, whereas we have seen that the important folding was pre-Cretaceous.⁹

The Catskills have a base of intensely folded Silurian strata, on which lie unconformably only slightly disturbed marine Devonian, and probably

⁹ Personal communication from Prof. E. W. Berry. See also Bowman: The Andes of southern Peru.

Lower Carboniferous, strata. Therefore there was depression after the folding of the Silurian strata, and later elevation without folding. Nearly the same history applies to the Blue Mountains of southeastern Australia. Nearly horizontal Carboniferous and other deposits, some of them marine, rest unconformably on strongly folded Devonian. The mountains are separated from the coastal area by a great monoclinal flexure. Their topography resembles the mesa topography of the western United States.

If we approach the Himalaya Mountains from the south we pass over the great alluvial plain of the Ganges, consisting of fluviatile deposits horizontally stratified. This plain is limited on the north by the sub-Himalaya or Siwalik Mountains, about 3,000 feet high, the boundary being supposed to be a fault. The Siwaliks consist of the same kind of material as the Ganges plain and evidently once formed a part of it. The strata, of middle and late Tertiary age, have been considerably folded and faulted. Beyond the Siwaliks, and separated from them by the great and nearly vertical main boundary fault, rise the Lesser Himalayas to a height of 12,000 to 15,000 feet. They consist of crystalline and stratified rocks, apparently very old, and are much more folded and crushed and are greatly metamorphosed. Beyond these again a sudden rise brings us to the culminating Central Himalayas, which are largely crystalline and appear to have suffered still more crushing. The Himalayas, therefore, rise from the plain by one short and two large steps. Many faults, principally parallel with the trend of the range, occur over the whole range; nearly all are reverse faults and are very steep. They seem to have been formed in roughly progressive order from the central region to the southern border. All parts of the range have suffered compression, strong in the heart of the range and considerably less in the weak Siwaliks.

The intense foldings and dislocations of the Himalayas could not have been produced in the present position of the rocks; for not only is there no sufficient buttress on the south to sustain the necessary pressure, but the folding of the strong rocks of the Lesser Himalayas suddenly becomes much less as we cross the main boundary fault into the weak strata of the Siwaliks. The pressure could not have diminished suddenly at a fault surface, nor could the compression of the strong rocks be less than that of the weaker under the same pressure. We conclude that the foldings and some faulting of the Himalayan rocks took place before their elevation, when they were continuous with the bedrock of the Ganges basin, and that the folding continues under that basin, probably dying out to the south, much as the Appalachian folds die out to the west. Hayden, from an examination of the Himalayan rocks themselves, con-

cludes that they have passed through many periods of intense folding, and that they may be a continuation of the Precambrian Purana rocks of the Peninsula.¹⁰

For the same reasons the Siwaliks must have been compressed before they were elevated, and their folds must continue in the lower beds of the Ganges basin.¹¹

The many steep faults, with a reverse attitude, show that the Himalayas were under horizontal pressure when the movements on the faults took place: indeed, the folding of the late Tertiary strata of the Siwaliks shows existence of horizontal pressure after they were deposited: but the small hade of the faults also shows that vertical forces were dominant in causing the uplift.¹²

Hayden tells us that the Lesser Himalayas are a dissected peneplain: and a peneplain could not be raised by compression without entirely obliterating its character. It must have been lifted by vertical forces.

These considerations lead us to the conclusion that the Himalayas were not raised to their present altitude by the compressional forces which folded their strata, but that the folding occurred at an earlier period, and the elevation came later, as the effect of vertical forces. We can picture the following order of events: Strong compression at several periods, with folding and faulting of the older rocks when at a lower level: elevation of the chain by successive steps, with displacements along the steep faults: great fluvial erosion, depositing the lower beds of the Ganges plain, of which the present Siwaliks formed a part: further folding, involving these lower beds, but probably not the strong Himalayan rocks: vertical movements, raising both the central mass and the Siwaliks to their present positions: continued erosion in the mountains and deposition in the plains.

The great steep faults between the Alps and the Po Valley and on the west side of the Wasatch Mountains show that these ranges also owe their elevation, at least in part, to vertical forces.

This brief review embraces the most important mountain ranges in the world, and shows beyond question that they were raised up and not squeezed up, and that the time of their elevation was distinctly later than the time of folding. The same conclusion could be extended to many

¹⁰ H. H. Hayden: Notes on the relationships of the Himalaya to the Indo-Gangetic Plain and the Indian Peninsula. Records of the Geol. Survey of India, 1913, vol. 43.

¹¹ This basin bears a striking resemblance to the Appalachian trough, as worked out by Hall. We wonder if it represents the early stages of a great mountain chain which will be a successor of the Himalayas.

¹² R. D. Oldham has reached the same conclusion. Manual of the Geology of India, second edition, p. 474.

other ranges; for wherever we find at high altitudes peneplains or marine strata not folded, wherever we find mountain ranges with folded and distorted strata extending to their lateral boundaries, or ranges limited by normal faults, we may be sure that the elevation was due to vertical and not to horizontal forces.

The above facts militate against the idea that mountain ranges are due to compression resulting from the cooling of the earth; for the compression would be greatest at the surface, and many ranges have been raised without compression of the strata.

RELATION OF ISOSTASY TO FOLDING AND UPLIFT

The objection to the principle of isostasy, due to the belief that mountain ranges were elevated by horizontal compression, is seen to be invalid. It must not be supposed that isostasy in any way contradicts the well authenticated fact that folded mountain ranges have been greatly compressed horizontally; it merely denies that the great heights of mountains are due to this compression. It is a necessary corollary of the principle of isostasy, in conjunction with observations on the deflection of the plumb-line and the intensity of gravity, that the great vertical movements are due to changes in the density of the underlying mass, though we do not know what causes these changes. Isostasy must not be blamed because it does not explain why the matter under mountain ranges changes its density. The explanation must be sought in totally different lines of investigation. Isostasy is no more capable of explaining it than the principle of hydrostatic equilibrium is capable of explaining the difference in the densities of oil and water.

When combined with geological observations, isostasy presents the following picture of the course of events leading to a folded mountain range: After the accumulation of sediments to a considerable thickness, forces compress and fold the strata. This necessarily increases the amount of matter in the compressed region and would naturally cause some elevation of the surface. On account of the disturbance of the isostatic equilibrium, forces are brought into play which cause the region to sink and drive out matter from below. When the equilibrium is reestablished the region would be slightly higher than before, on account of the accumulation of the lighter surface rock, which lowers the average density of the mass. How great the actual elevation, due to compression, may be depends on the amount of compression and on the relation between the rates of compression and of readjustment of equilibrium. We do not know this relation, and, in the absence of observations of deflection and

gravity during the time of compression, we can gain an idea of it only through geological observations which distinguish between folding and uplift. Finally, the uplift of the underlying mass raises the region into a true mountain range.¹³

There is nothing in the principle of isostasy that militates against the coexistence of the expansion and consequent elevation and the folding, but geological observations show that the elevation, now existing in the cases cited above, has occurred at a distinctly later date than the folding. The interval between them has been long enough, in some cases, to allow a peneplanation of the surface; in other cases depression to well below sealevel has occurred and considerable thicknesses of sediments have been deposited in this interval.

ISOSTASY AND PENEPLANATION

It has been argued that during a state of peneplanation there has been no movement of the area, which was being gradually worn down by erosion, and therefore if it were in isostatic equilibrium before the erosion, it could not be afterward. But this is begging the question. According to the principle of isostasy, there must be, during the erosion, an influx of matter below (with an unknown lag), to keep up the equilibrium. This would cause a slow elevation of the region, but at a rate less than the lowering by erosion, because the inflowing matter would have a greater density than the surface matter removed. The lag could not be very great, for regions now undergoing active erosion do not show a material defect or excess of gravity.¹⁴ I know nothing that renders this point of view unsound.

ISOSTASY AND THE RIGIDITY OF ROCK

The argument that rock under pressure is too rigid to permit the movements called for by the principle of isostasy is based on the excellent

¹³ The conviction that folding and elevation are merely different aspects of the same event has become so ingrained that the two words are often used almost as synonyms, and it is sometimes difficult to decide whether a writer is recording a true uplift or merely folding. It is very important that field geologists should distinguish between the two processes.

Dr. Rollin T. Chamberlin has attempted to determine the depth to which compression has extended on the assumption that the elevation was entirely due to compression (*Jour. Geol.*, 1910, vol. xviii, pp. 228-251; and 1919, vol. xxvii, pp. 225-251); but if the ideas of the present paper are right, his assumptions are wrong. He considered the possibility of simple vertical uplift, but decided that it did not have an important part in the elevations he measured. I do not think his observations justify his conclusions, for I have been unable to make the details of the movements he deduces fit his general idea.

¹⁴ S. G. Burrard: *Geog. Jour.*, 1921, vol. lviii, p. 215.

experiments of Adams and Bancroft.¹⁵ They showed that, under the conditions of their experiments, the differential pressure "required to produce a pronounced movement" in the rock increased markedly with the hydrostatic pressure. Under hydrostatic pressure equivalent to the weight of 4.2 miles of rock, the deformation of marble required an additional differential pressure equal to the weight of 11 miles of rock, and granite required more than twice as much. These forces are so great that, if the results of the experiments were directly applicable to the earth, the principle of isostasy would have to be abandoned. But are they directly applicable?

High temperature is very efficient in reducing the strength of solids; the experiments of Adams were carried out at ordinary temperatures.¹⁶ Time is also a very important factor; the longest of the experiments lasted only six hours. Every one who makes delicate measurements dependent on elastic forces knows the difficulty encountered on account of permanent sets, and that the amount of these sets depends on the duration of the stress. Adams found that a piece of marble in the shape of a lathe, supported at its ends like a beam and weighted in the middle, yielded continuously after a certain weight had been added.¹⁷ (The tensions brought into play may have had some influence on the result.) Indeed, the slow yielding of many substances to continued forces, much smaller than are needed for deformation in a short time, is too well known to be dwelt on; and it must be remembered that the total displacement is the sum of the distortions of the parts and may be considerable even when the latter are small.

Let us turn to geological observations. Strata have been intensely folded and distorted; marble slabs in cemeteries, supported at their ends, have bent down in the middle in the course of one or two centuries, and crystalline rocks have been greatly compressed. It matters not that the distortion of crystalline rock has been referred by petrographers to recrystallization; the only important thing in this connection is that considerable displacements have taken place. Some of these movements may have required great forces, but the marble certainly did not. Molten lava, which surely comes from a depth of several miles, and reaches the earth's

¹⁵ Frank D. Adams and J. Austin Bancroft: On the amount of internal friction developed in rocks during deformation and on the relative plasticity of different kinds of rocks. *Jour. Geol.*, 1917, vol. xxv, pp. 592-637.

¹⁶ In his earlier experiments, Adams used temperatures as high as 550 degrees. He was then studying the effect of pressure in closing small cavities in rock. An experimental contribution to the question of the depth of the zone of flow in the earth's crust. *Jour. Geol.*, 1912, vol. xx, pp. 97-118.

¹⁷ Frank D. Adams and Ernest G. Coker: The elastic constants of rocks. Carnegie Institution of Washington, Publication 46, 1906.

surface at a temperature not greatly above its melting point, could hardly have suffered much cooling in the last few miles of its course, and therefore must have been in, at least, a very plastic condition when under considerable pressure and at no extraordinary temperature.

It does not seem legitimate to infer from Adams's experiments that rock some miles below the surface can not yield to long continued and not very great forces.

CONCLUSION

If we reject the principle of isostasy and its corollary, that mountains are raised by the expansion of the underlying mass, we must believe that they are raised by material being forced in under them from below; for it has been shown that many ranges are not raised by simple compression. This brings with it certain implications. It grants the possibility of subterranean flow and weakens one of the objections to isostasy. As the mountains of the present are in isostatic equilibrium with the rest of the world, the region where they now are must, before the influx, have been in defect by an amount at least equal to the mass of the mountains now above their former level; and this defect must have existed in a region where not only had thousands of feet of sediments been accumulated, but into which still more matter had been forced by the earlier folding. No such defect exists anywhere in the world at present. The plain of the Ganges, which resembles closely the Appalachian trough shortly before the folding, shows no defect of gravity that is not due to the local low density of its deposits. Is it reasonable to believe that a region where matter has been massed to such an extraordinary amount should be the very region to be so extraordinarily in defect? And that, at the time of elevation, exactly the right amount of matter to produce isostatic equilibrium should be forced into it? And, moreover, that there was a near-by region with just the right excess of matter, which it gave up to the mountain area by subterranean flow, remaining itself in equilibrium?

If we refuse to apply the principle of isostasy to the past, we reject the principle, so fruitful in the history of geology, that we must interpret the past in the light of the present. This principle does not require us to assume that conditions were always as they are now, but it does require us to apply to the past the processes and principles now in force, and only to modify them in the face of definite evidence. And what definite evidence is there opposed to the general principle of isostasy? I know of none.

ISOSTASY AND APPLIED GEOLOGY ¹

BY JAMES F. KEMP

(Read in full before the Society December 29, 1921)

CONTENTS

	Page
Fundamental relations.....	327
Isostasy and coal formation.....	327
Illustrations of isostatic adjustment in engineering work.....	328
Isostasy and oil geology.....	329
Isostasy and fault production.....	330
Mineral veins and intrusive igneous masses.....	330
Relations to limiting depth and conclusion.....	331

FUNDAMENTAL RELATIONS

The relations of isostatic readjustment with mining geology or with other applications of the science to problems in professional practice are those of large, general character, of fundamental conceptions, and of great first causes, rather than of special service in particular cases. When an ore body is cut off by a fault and the mining geologist has to decide what to do next in order to find the missing part, the conceptions based on isostasy are not of immediate help; but if in his daily work the thoughts of the mining geologist turn to the cause of the faults with which he has to deal, isostatic readjustment must of necessity come into his field of view in a fundamental way. In responding to the request of Mr. Bowie to add a few pages of reflections on these questions to the symposium, I am compelled by the very nature of the case to treat the subject in the large way. I may in the end ask more questions than I shall answer.

ISOSTASY AND COAL FORMATION

One of the most important questions with which we have to deal in economic geology relates to coal. Years of study have now established

¹ Manuscript received by the Secretary of the Society January 18, 1922.

This paper is one of a series composing a symposium on isostasy.

beyond peradventure that coal is of vegetable origin, and that in the vast majority of cases its parent vegetation has grown where, on falling down or otherwise accumulating, the carbonaceous matter was buried beneath a protecting cover of fresh water.

Yet the swamps of necessity flourished along an irregularly subsiding shoreline, such that, after slow accumulation, marine waters or great bodies of fresh water could, when suddenly accelerated subsidence took place, rush quickly over the swamp and bury its peat under rapidly growing fragmental sediments. Sometimes the rush was very rapid. The upstanding tree trunks in the Nova Scotia Coal Measures, which Sir J. William Dawson described many years ago, were entombed before they even fell over. In the hollow stumps of some the very insects which inhabited them were fossilized. After the rush a pause often ensued and a new swamp started. The peat accumulated again until renewed subsidence, with the inrush of fragmental sediments, buried it as before. We can only interpret our coal strata as those characteristic of flat coastal plains, with swamps of fresh water and a not very distant ocean or huge body of fresh water.

It is reasonable to conclude that along the coastline behind which the coal swamps grew deltas and offshore deposits were rather rapidly accumulating. During the time required for the accumulation of the peat for a coal seam the rigidity of the local crust of the earth held the relations steady. When the accumulating load overcame the rigidity and the shore sank, the raw material of the coal seam was submerged and buried. In the broad range of geological sections there are few which furnish such good illustrations of what one might almost call the normal progress of isostatic adjustment. In the end, however, coal seams almost always come to rest in a series of gentle or more violent folds, such as might result when the full oscillatory course had been run and isostatic balance had been so seriously disturbed by offshore sedimentation as to lead to final crumpling.

ILLUSTRATIONS OF ISOSTATIC ADJUSTMENT IN ENGINEERING WORK

Extremely suggestive illustrations on a small scale are often afforded when engineers make a fill for a railway embankment on a soft support. The well known Lucine cut-off filled in by the Southern Pacific Railroad across an arm of the Great Salt Lake is an instance, but many others are known. In former years the spoil from various excavations in New York City was used as fill on the salt meadows of Pelham Bay Park. It produced from the soft turf and mud beautiful anticlines and synclines for

an impressive distance. The readjustment from overloading a soft supporting bed habitually is manifested in a series of diminishing waves on each side of an embankment. These cases are not entirely parallel to accumulations on the continental shelf, because in the latter instance the gentle folds must chiefly develop on the landward side alone. Probably one would go too far if one ascribed all the upheaval of folded mountains to isostatic readjustment, but in appealing to the doctrine we certainly turn to a true and dependable cause, as far as it is reasonably to be employed.

ISOSTASY AND OIL GEOLOGY

The applications of geology to the location of subsurface pools of petroleum and natural gas, a use which we owe primarily to our honored President of last year, Dr. I. C. White, are all based on the identification of the high points of anticlinal folds. The applications were first made 35 years ago to the Appalachian anticlines of western Pennsylvania and West Virginia. These folds are strong and pronounced, but in the last twenty years scientifically guided exploration has spread to the Mid-continent and Coastal Plain oil fields, where the anticlinal and monoclinal folds are often so slight as to require instrumental surveys of a key stratum to positively locate their high points. In thinking over the causes which might lead to such gentle upheavals, one can not help harking back to isostatic readjustment. Indeed, this suggestion has already been made by M. Albertson, now of Shreveport, Louisiana. Mr. Albertson presented a very interesting paper at the annual meeting of the American Institute of Mining Engineers last February. It seems that he had formerly lived at Cobalt, Ontario, and had observed the pumping out of Kerr Lake, so that exploration for silver veins might go on safely beneath its former bottom. On the bottom was a soft, slimy, and weak mud, before any artificial load was contributed. Beginning with a railroad fill in 1903 and proceeding with accumulations of tailings from several mills and with washings, hydraulicked from over 500 acres by one of the mining companies, a series of artificial deltas were produced so as really to constitute isostatic experiments on a large scale. In the old mud of the original bottom several domes of varying sizes resulted, and as the overlying load of water was pumped off the older ones grew larger and others began successively to appear. Mr. Albertson acutely compares them to the gentle domes of the Gulf Coastal Plain and the Mid-continent field and draws the analogy between coastal sedimentation and neighboring shore upheaval. Indeed, the analogy is extremely close with isostatic re-

adjustment. We have the pumping out of the water, analogous to the removal of load by erosion. We have the introduction of tailings and debris in small deltas. We have finally the bulging in domes because of slow, subsurface transfer of plastic material, the domes rising at a modest distance from the deltas. Change the scale to that of nature and we have a very suggestive series of observations.

When we find isolated domes, or short anticlines with relatively small axial length, or upheavals caused by the upward flowage of relatively plastic rock-salt, we can not help surmising that the pressure from coastal overloading has been transmitted by deep plastic flow and has produced the bulges. Except for this cause, localized upheavals are difficult to explain otherwise than by igneous intrusive masses, probably laccolithic in shape.

ISOSTASY AND FAULT PRODUCTION

The slow, viscous flow of rock-matter near or just below the 71-mile limit, or in the asthenic zone of Barrell, can not well take place in great volume without transmitting strains to the upper world. Possibly the faults which are so often the locus of mineral veins, and especially of veins not visibly or apparently connected with igneous intrusions, may in some way be connected with these interior transfers. Possibly, also, the much greater number of faults which, as we are daily learning with greater and greater emphasis, are associated with many of our striking topographic features may also be caused by these transfers.

MINERAL VEINS AND INTRUSIVE IGNEOUS MASSES

The greater number of mineral veins, and especially those productive of ores, are now pretty well recognized to be associated with igneous intrusive masses. What we geologists who have from time to time to deal with them, or with the associated intrusive bodies, wish to know is some reasonable explanation for the uprising of the batholiths or laccoliths or sills or dikes from the depths. If the slow, deep-seated, viscous flow of rocks still solid, but yet highly heated, sometimes turns from horizontal movement to a journey upward, then we can understand that with diminishing pressure the vast masses may fuse, may finally come to rest within a moderate distance from the surface, and may part with dissolved gases. We shall thus have a reasonable explanation of a train of events one of whose end products is the mineral vein. If isostatic readjustment will furnish us with this extremely important fundamental conception, it will do us great service. The heavy deposition of sediment, perhaps at a re-

mote coastline, may upset the equilibrium of the crust, may initiate the slow lateral and upward transfer of rocks, and may produce the ultimate igneous intrusion with all its corollaries.

RELATIONS TO LIMITING DEPTH AND CONCLUSION

The 71-mile limit of isostatic equilibrium, or any similar and more accurately established limit, will then give us a fairly accurate conception of the depth where these changes initiate and a much more sharply defined range for somewhat speculative reasoning than we gain in any other way. But in connection with these matters I feel myself on much less stable ground than when speaking of coal basins and oil domes and am driven to ask questions rather than answer them.

FOLDING OF MOUNTAIN RANGES—THE ARGUMENT FROM
ISOSTASY¹BY SIR SIDNEY BURRARD²*(Read before the Society December 29, 1921)*

CONTENTS

	Page
Introduction.....	333
Mountain formation by vertical expansion.....	334
Geological structure of Himalayas.....	335
Relation of isostasy to mountain formation.....	335

INTRODUCTION

The hypothesis that mountain ranges have originated from the shrinkage of the earth's core away from its crust and from the consequent wrinkling of the crust has not met with support from geodesists in India. In 1858 Pratt's investigations of Himalayan attraction and compensation raised serious objections, and these were subsequently strengthened by the brilliant writings of Dutton.³ Pratt was a mathematician and Dutton was a geologist. Pratt regarded the subterranean compensation of the Himalayas as a proof that these mountains had arisen from below by the vertical expansion of rocks in the crust. But even before Pratt had published his conclusions the Himalayan geologist, Strachey, had put forward an opinion, based on geological grounds, that the origin of the Himalayas had been vertical uplift.⁴ And the idea of a planetary core contracting independently of its outer shell was forcibly opposed by Osmond Fisher, also a geologist.⁵

¹ Manuscript received by the Secretary of the Society November 17, 1921.

This paper is one of a series composing a symposium on isostasy.

² Introduced by William Bowie.

³ Philosoph. Trans. Royal Society London, 1858.

Bull. Philosoph. Soc. Washington, vol. xi, 1892, pp. 51-64.

⁴ Quart. Journ. Geolog. Soc., vol. vii, 1851, p. 292.

⁵ Physics of the earth's crust.

MOUNTAIN FORMATION BY VERTICAL EXPANSION

This difficult question has been recently discussed by Dr. William Bowie, in his paper,⁶ "Relation of isostasy to uplift and subsidence." The conclusions which Bowie has drawn from a study of the Appalachian system are a helpful contribution to the understanding of the Himalayas. Bowie writes:

"We are led to the conclusion that the cause of the mountain formation is a local one, and the only local cause seems to be a change in density in the column. This change must have been the result of a local expansion in the isostatic shell under the sedimentary material which was thrown up to form the mountain mass."

This explanation appears very applicable to the Himalayan system. The primary feature of mountains is their height, and the highest points of the Himalayas are mainly granitic. Sir H. Hayden, the late Director of the Geological Survey of India, writes:⁷

"Almost all the peaks of 25,000 feet and more are composed of granite, gneiss, and associated crystalline rocks. The great peaks lie on continuous elevated zones of granite and crystalline rock. The great central gneissose rocks of the Himalayas were proved by General McMahon to be an intrusive granite foliated by pressure";

and again the same eminent authority writes:

"During the development of the Himalayas as a mountain range vast masses of granite welled up from below."

If this granite range had been standing alone, its vertical origin would never have been questioned, but the sedimentary rocks on its southern flank have been folded and elevated. On the other hand, if these folds had been standing alone and had been unaccompanied by the granitic outbursts, geologists would have felt little doubt that the mountains had been raised by horizontal compression of the crust. The granite outbursts and the horizontal folds are in juxtaposition. The problem now presented to us is: Has the vertical uplift of the granite been incidental to the horizontal compression, or has the folding been incidental to the vertical rise of the granite?

Bowie holds that the folding has been incidental to the vertical uplift. A strong argument in support of this contention is that the folded sedimentaries are inferior in height and mass to the granite intrusions with which they are in contact.

⁶ American Journal of Science, vol. ii, July, 1921.

⁷ Sketch of Himalayan geography and geology, 1907, pp. 7 and 8.

GEOLOGICAL STRUCTURE OF HIMALAYAS

If we examine the geological sections drawn across the Himalayas, the granite appears to be the main factor;⁸ in large-scale sections of subsidiary features much folding has been shown, but these folds are superficial and local;⁹ their span varies from a furlong up to a mile or two, while the base of the Great Himalayan Range is 40 or 50 miles wide; by no stretch of imagination can the Great Himalayan Range be described as a fold of the earth's crust.

Moreover, even among the sedimentary rocks their folding is not so much in evidence as their tilting and faulting; the strata are neither arched nor curved to the same extent as they are tilted and fractured. On the flank of the Himalayas the inward dip of the strata toward the main range without curvature is a remarkable and impressive phenomena. Bowie's explanation of the Appalachian system appears to me to fit the observed facts of the sub-Himalayan zone; I refer to the following passage:

"When uplift begins it is probable that it takes place in different sections of the area affected at different rates and at different times. There would be more resistance to the uplift in some parts of the area than in others. . . . It is conceivable that in the process of uplift in a large area we should get distortions such as are found in most areas of mountain uplift.

"We have evidence that much material of the earth has been uplifted without distortion. The great plateaus of the West have their strata practically horizontal, and in some cases they extend for miles."¹⁰

RELATION OF ISOSTASY TO MOUNTAIN FORMATION

No discussion of the origin of mountains is complete without full consideration of the arguments from isostasy; it is the theory of isostasy that has shown us the expansions and contractions of rock masses in the crust. So strongly do I realize our great debt to this theory that I wish to give a warning against the risks of misapplying it. Any discovery that a theory is being misapplied is liable to bring it into unfair discredit with laymen and to postpone its acceptance. The lesson taught by the theory of isostasy and founded on researches initiated by Hayford is that the rock of the crust undergoes changes of density which not only produce changes of surface elevation, but which also maintain the equilibrium of

⁸ Sketch Himalayan geography and geology, Hayden's sections, plate xxxviii, Hayden's section of Kinchinjunga.

⁹ Middlemiss's sections, Geological Survey of India, vol. xxiv; Hayden's sections, Geological Survey of India, vol. xxxvi.

¹⁰ American Journal of Science, vol. ii, July, 1921, p. 17.

the crust by compensating at depth the effects of surface erosion and deposition.

But a different form of conclusion has been drawn from the theory of isostasy, one which has not been based on geodetic observations. In company with other geodesists, I have myself in the past fortified my convictions by means of this very conclusion of which I am now so doubtful. It has been argued that the theory of isostasy excludes all hypotheses which give to mountains additional mass, and that therefore mountains can not have originated from horizontal folding, because horizontal compression and folding imply additional mass pushed in from the sides.

Of recent years geodetic observations have shown that however rock-mass may be moved about over the surface of the earth, the changes in its surface position become compensated at depth. If mass is eroded from a mountain peak, the loss from erosion becomes locally compensated, and if mass is deposited in alluvial beds, the additional load becomes compensated; that is to say, when rock is moved horizontally over the earth's surface from one place to another, the horizontal transfers of matter are compensated by changes of density in the crust.¹¹ From gravity observations taken at stations near the mouths of the Mississippi, the Ganges, the Irawadi, and the Po, it appears that the deltaic deposits of great rivers are compensated.¹² In all probability the deltas of the Nile and the Tigris will be found to be compensated, when the necessary pendulum observations have been made. These deltas are additional amounts of material brought in horizontally from the side, just as the folds of strata are. If these deltaic loads, brought in from one side, become automatically compensated, why should not loads which have been accumulated locally by folding be also compensated?

I agree with Bowie's contention that mountains can not have originated by folding, but I think that the hypothesis of the folding of strata will have to be challenged by its opponents on other grounds than that of isostasy.

¹¹ Hayford and Bowie: *Effect of topography and isostatic compensation upon the intensity of gravity*, 1912, p. 112.

¹² William Bowie: *Investigations of gravity and isostasy*, 1917, p. 84.

ISOSTATIC COMPENSATION CONSIDERED AS A CAUSE OF THRUSTING¹

BY ANDREW C. LAWSON

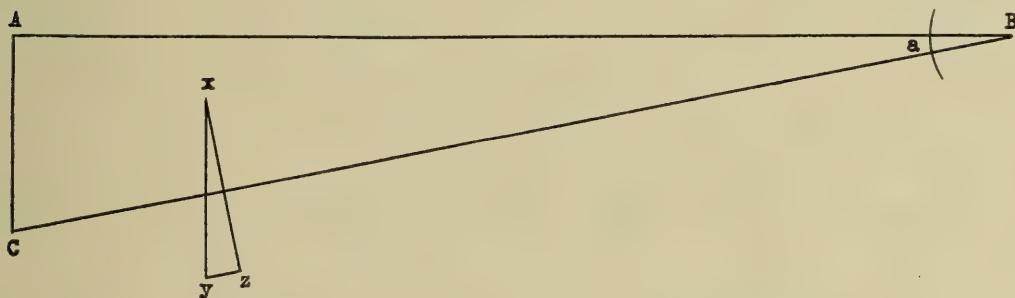
(Presented in abstract before the Society December 29, 1921)

CONTENTS

	Page
The limits of length of overthrust blocks.....	337
The limits of movement of overthrust blocks.....	341
Underthrusting.....	344
Compensatory flow and underthrusting.....	349

THE LIMITS OF LENGTH OF OVERTHRUST BLOCKS

If a rupture plane of low dip exist in the earth's crust emergent at the surface, and if a stress exist in the overlying prism which tends to move it toward the emergent side, the movement is restrained by the friction of the surfaces in contact on the rupture plane. If, further, the stress

FIGURE 1.—*Diagrammatic Representation of a Thrust Block*

AB, surface of the earth; BC, thrust plane.

be due to a pressure applied from without to the cross-section of the prism, then, in order that the prism may move, and so be thrust over the underlying rock-mass, the pressure must exceed the friction on the rupture plane. If the stress be tangential in direction and uniformly dis-

¹ Manuscript received by the Secretary of the Society November 14, 1921.

This paper is one of a series composing a symposium on isostasy. In the absence of the author, it was presented by H. F. Reid.

tributed in the cross-section of the prism, then the limiting length of the prism which may be moved is determinable; since, when the stress necessary to overcome the frictional resistance becomes greater than the strength of the material of the prism, a new rupture will be inaugurated.

Let ABC be a wedge-shaped prism of the earth's crust, AB being the surface of the earth, and BC a fracture plane which has been established at the initiation of a thrust.

W = weight of prism.

w = weight of cubic foot of rock.

f = coefficient of friction.

P = component of W normal to BC.

G = component of W parallel to BC.

G_1 = horizontal force equal to G.

F = frictional resistance.

F_1 = horizontal force equal to F.

S = crushing strength of rock.

$$W = \frac{AB \cdot AC \cdot w}{2} = \frac{AB^2 \cdot \tan a \cdot w}{2}.$$

Make xyz similar to BCA and $xy = W$.

$$\text{Then } P = xz = xy \cos a = W \cos a = \frac{AB^2 \cdot \tan a \cdot \cos a \cdot w}{2} = \frac{AB^2 \sin a \cdot w}{2}$$

$$F = f \cdot P = \frac{f \cdot AB^2 \cdot \sin a \cdot w}{2}$$

$$F_1 = \frac{F}{\cos a} = \frac{f \cdot AB^2 \cdot \sin a \cdot w}{2 \cos a} = \frac{f \cdot AB^2 \cdot \tan a \cdot w}{2}$$

$$G = yz = xy \sin a = W \cdot \sin a = \frac{AB^2 \cdot \tan a \cdot w \sin a}{2}$$

$$G_1 = \frac{G}{\cos a} = \frac{AB^2 \cdot \tan a \cdot w \cdot \sin a}{2 \cos a} = \frac{AB^2 \cdot \tan^2 a \cdot w}{2}$$

$$F_1 + G_1 = AC \cdot S$$

$$\text{that is, } \frac{f \cdot AB^2 \cdot \tan a \cdot w + AB^2 \tan^2 a \cdot w}{2} = AB \cdot \tan a \cdot S$$

$$AB = \frac{2S}{(f + \tan a) w}.$$

As the angle a becomes larger, the expression $(f + \tan a) w$ increases, so that the value of AB decreases.

That is to say, the greatest possible length of a thrust-block, measured in the direction of the thrust-movement, is for the case where the thrust-plane is horizontal.

This value of AB varies with the thickness of the prism in so far as the crushing strength varies with depth. But we are concerned only with the minimum value of S, namely, that at the surface, since when the

stress exceeds this value a new rupture will start at the surface and be propagated downward.

For any given angle a which a thrust-plane makes with the horizon we arrive at a limiting value for AB by assuming concrete values for S , w , and f :

w may be taken as .075 ton per cubic foot;

S , for the strongest rocks at the surface, may be taken as 15 tons per square inch, or 2,160 tons per square foot.

The value of f is more debatable. Under laboratory conditions for the determination of engineering data, the maximum value of f for rock on

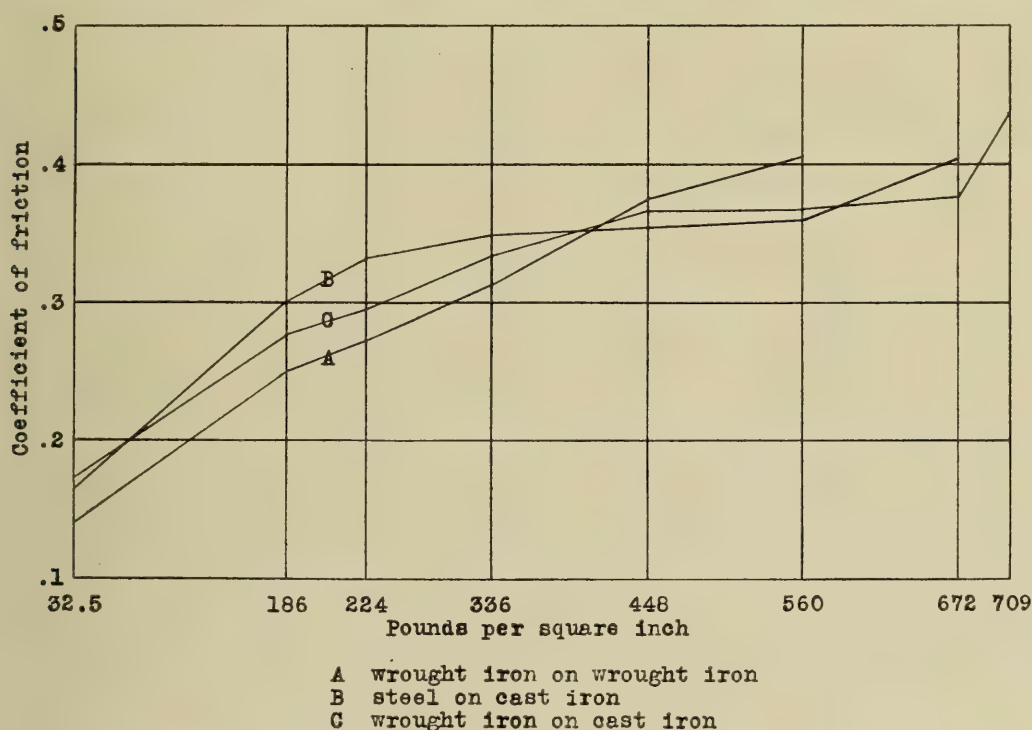


FIGURE 2.—Diagram to show the Increase in the Coefficient of Friction with increasing Pressure. (After Rennie.)

rock is about .65. We may assume .5 as a fair figure for this quantity, as ordinarily determined; but the value of the coefficient of friction both in the laboratory and in nature varies with varying conditions. Certain experiments reported in engineering handbooks indicate that up to the limit of abrasion the coefficient of friction increases with increasing pressure.

The graph in the accompanying diagram, figure 2, constructed from results obtained by G. Rennie,² shows the rise of the value for the coefficient of friction with increase of pressure.

² John C. Trautwine: The civil engineer's pocket-book, 1900, p. 374b.

In nature the pressures are very commonly such that, when movement occurs on a rupture plane, the limit of abrasion is exceeded, as is shown by the prevalence of gouges and fault breccias. The frictional resistance to movement is not the same when the opposed surfaces are dry as when they are wet, nor is it the same when the surfaces are polished as when they are rough. I have found experimentally that when polished granite is pulled horizontally over polished granite with a bed of fine dry sand between the two surfaces, the figure obtained for the coefficient of friction is twice as great as when the polished surfaces are in direct contact; that when the sand is damp the value is two and a half times the value found when no sand is used, and that when the sand is saturated with water the value is three times as great. These results indicate that when the pressure is sufficient to develop a fault breccia the frictional resistance is thereby increased. When, however, a fault breccia is pulverized to a gouge and then saturated with water, the gouge may, perhaps, act as a lubricant. Gouge, moreover, may be developed directly by abrasion without the intervention of the condition of coarse breccia; but movement on an initial rupture is antecedent to the development of gouge, and this early movement is, therefore, not promoted by lubrication.

In the case presented I have postulated an existent rupture without qualification as to the presence or absence of a gouge lubricant and without consideration of its mode of origination. Such a rupture, however, could only occur in the earth's crust as an expression of the relief of strain, which had accumulated to the limit determined by the strength of the rocks. The stress inducing this strain may have been applied to the prism above the consequent rupture plane, in the direction toward its emergence, or to the region below that plane in the opposite direction. In the case before us consideration is limited to the first of these two possibilities. In such a case it is presumable that the stress in the superficial prism of the crust, having just exceeded the strength of the rocks at the surface and initiated a rupture there, would immediately be relatively intensified in the still unruptured region, so that the rupture would be propagated rapidly back and down until it was partially relieved in the whole of the prism affected. The residual stress would be measured by the frictional resistance on the rupture plane thus established. It is thus conceivable and probable that an intact prism might be detached from the crust on its lower side; but with the extension of the rupture plane frictional resistance would increase till it balanced the motive stress. In the development of such a rupture the amount of movement would be slight, being limited to that necessary for the first culmination of strain. This movement would be greatest at the surface and would diminish to

zero toward the origin of stress. With this limited movement there would be small opportunity for the development of a gouge which might serve as a lubricant. Such attrition as might occur would probably result in a breccia whereby the frictional resistance would be increased.

From these considerations as well as the probability that the coefficient of friction increases with increasing pressure, it is assumed that the coefficient of friction on the rupture plane postulated is not less than that determined for similar rocks experimentally under slight pressures.

By substituting the assumed values for S , w , and f in the equation

$$AB = \frac{2S}{(f + \tan a) w},$$

we may obtain a concrete expression for AB —that

is, the limiting value for the length of an overthrust wedge of the crust, measured in the direction of the thrusting for any angle of thrust. Since f is the doubtful factor in the equation, the doubt may be recognized by adopting a series of values for that factor.

Limiting Values for Length of overthrust Prism

a	$f = .5$	$f = .4$	$f = .3$
2°	20 miles	25 miles	32 miles
5°	18 miles	22 miles	26 miles
10°	16 miles	19 miles	23 miles
20°	12 miles	14 miles	16 miles

In arriving at these values for AB , S has been taken at 15 tons per square inch, or 2,160 tons per square foot, which is the maximum crushing load for the strongest rocks at the surface. Any diminution of this factor would proportionally reduce the value of AB . It is probable that the proper value for S is between the crushing load and the shearing strength, and this would be notably less than the value assumed.

THE LIMITS OF MOVEMENT OF OVERTHRUST BLOCKS

The elastic rebound theory of faulting teaches that when a slip occurs on a fault, both sides of the fault move suddenly, each in an opposite direction, and that the amount of movement is limited to that necessary to relieve the elastic strain in the rocks. The stress which generates the strain may be persistent, so that by repetition of relief by slip the aggregate relative displacement may be large. The relief from strain at every slip may, and probably does, involve an equal amount of fling on each side of the fault; but the aggregate effect of repeated slips may be that of a *mobile* block moving past a *passive* block, the former advancing with each slip, while the latter simply oscillates between the positions of strain

and relief. In geological studies it is of importance to discriminate between the mobile and the passive blocks, since when we can do this we know the direction of the origin of stress. In the case of a real overthrust the upper block is the mobile side of the fault, and it would seem that the stress which is the cause of the progressive advance of the block could scarcely be applied otherwise than horizontally and fairly uniformly to its cross-section. Any other non-uniform application of the stress would probably result in a limiting value for AB less than that found above.

For a real overthrust, therefore, it appears that the limiting length of the overthrust prism in the direction of the force applied is between 20 and 30 miles when the thrust-plane is nearly horizontal, and less than this if the thrust-plane is inclined. It follows from this limitation on the length of overthrust blocks that, if the stress which causes the displacement persist, relief of renewed strain can only be effected by a new

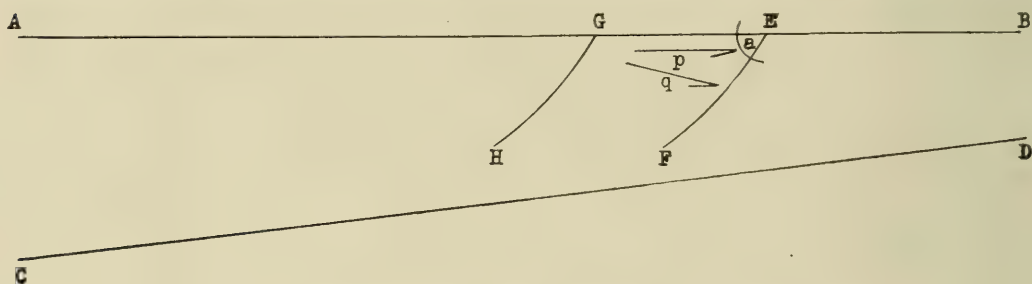


FIGURE 3.—*Diagrammatic Representation of a Thrust Block*

AB, surface of the earth; CD, thrust plane; EF and GH, successive curving thrusts due to failure of thrust block.

fault rupture situated nearer the origin of the stress. In this way, by a prolongation of the process, an imbricated structure may be produced, the fault blocks overriding each other in orderly succession like tiles on a roof.

This limitation on the length of an overthrust block, measured in the direction of the thrust, places a still more important limitation on the amount of movement by real overthrusting on a fault plane; for if it be true that 20 to 30 miles is the limiting length of the overriding block, then any displacement relative to the passive block—say, for example, one mile—must affect the whole of the block, except for slight differences in the condition of compressive strain; that is to say, the end of the block nearer the origin of stress must move approximately as much as the more remote end. But this could only happen if the ground still nearer the origin of stress were also moving, and this implies a frictional resistance to movement in excess of the strength of the rocks, as has been shown in arriving at the limiting value of AB. It seems, therefore, mechanically

impossible, *a priori*, that a single intact prism of the earth's crust could move more than a small fraction of a mile by real overthrusting as a mobile block past a passive underlying block.

In the diagram, figure 3, let AB be the surface of the earth and CD an assumed rupture plane on which the prism ABCD tends to move to the right by a stress from the left. Let EF be the new rupture induced by a stress less than the frictional resistance on CD, but greater than the strength of rocks at the surface. The rupture EF will presumably start at the surface, where the strength is least, and be propagated downward. There will be relative displacement on EF, but this will be limited to elastic rebound and therefore will be small in amount. At first EF may be small, but if the stress be persistent the strain will, after the first relief, again accumulate to an excess of the strength of the rock and the rupture will be extended. Finally, by repetition of this process, the rup-

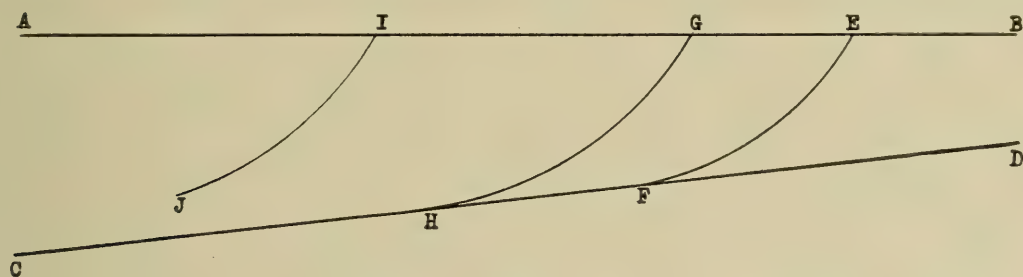


FIGURE 4.—*Diagrammatic Representation of a Thrust Block*

AB, surface of the earth; CD, thrust plane; EF, GH, IJ, successive thrusts due to failure of thrust block.

ture EF will reach a limit, determined by the angle a , at which friction on this plane will also inhibit movement, and no farther extension of the crack can take place. Further accumulation of strain can then only be relieved by another rupture, as at GH, and so on.

Here two cases are possible as to the relation of the successive ruptures EF, GH, and so forth, to the original fracture CD: In accordance with engineering experience, these ruptures will make a high angle with the direction of stress—that is, with the horizontal. The horizontal distance between E and F, and therefore EF itself, is a function of the angle AEF, becoming less as the angle is larger. Before reaching the limit of its possible length EF (and similarly GH, and so forth), it may encounter and merge with CD, as in figure 4; or, if CD be too far below the surface, EF, GH, and so forth, will terminate before reaching it, as in figure 3; but in neither case can there be large movement on the ruptures EF, GH, and so forth. It is to be noted, however, that, in the case where CD is limited in length and is shallow, so that the new highly inclined ruptures

merge with it, then the mobile prism becomes successively AEFC, AGHC, and so forth; and if a new rupture arise sufficiently near to C, CD may be extended down; but a limit to this extension will be reached when CD becomes too deep to be intersected by the later steep ruptures IJ, and so forth.

It appears, therefore, that in the case of real overthrust, where the lower is considered as the passive block and the upper as the mobile block, there can be no large relative displacement on any single block, owing to the fact that strain is relieved by a succession of limited ruptures and the development of an imbricated structure. It follows, of course, that the assumed lowly inclined rupture with which we started, if it exceed the limit found for AB, could not have been formed by real overthrusting.

In the diagrams, figures 3 and 4, the assumption is implied that the secondary ruptures EF, GH, and so forth, are curved, with concavity toward the origin of stress. The consideration underlying this assumption may be briefly stated: Prior to the inauguration of the rupture EF at the surface, the direction of stress is horizontal. If now this rupture be initiated for a depth, say, of one mile from the surface, and be inclined to the horizon, as engineering experience indicates it should be, then the angle which the new rupture plane makes with the direction of stress tends to be constant; but the moment that the first mile of rupture is opened and the strain in the upper part of the prism is thereby relieved, the direction of stress is changed from the direction indicated by the arrow p to that of the arrow q , in figure 3; and, since the angle tends to remain constant, the direction of EF, for the second mile of its extension, will change by the same angular amount. Since both the extension of EF and the change of direction of the stress are coincidentally progressive, EF will be curved and concave toward the origin of the stress.

UNDERTHRUSTING

We may now consider the case in which, for an assumed rupture of low dip in the earth's crust, the lower block is the mobile element and the upper the passive.

In the diagram, figure 5, let AB be the surface of the earth and CD the rupture plane. By assumption the region below CD tends to move toward the left by a stress from the right. In this case we may think of the stress either (1) as applied to the cross-section of the lower block, pushing it forward, or (2) as a gravitative stress, acting on every particle within the block, or (3) as applied to the bottom of the block by a viscous current.

1. If the force be applied so that the block is pushed, then the latter will behave much in the same manner as the upper block did when it was considered the mobile element, except that the strength of the rock will be greater and the limits of the secondary rupture will also be greater; that is to say, that the block below CD would be broken up with the development of an imbricated structure. The imbrication of the block below CD would, however, be restrained by the load of the block above it. If this restraint were overcome, the block above CD would be correspondingly broken, probably by normal faults; but as neither the imbrication of the lower block nor the breaking of the upper block, by reason of a stress applied as a push to the cross-section of the mobile block, would produce the phenomena of large thrusting, the case will not further be considered.

2. If the force be applied to all parts of the mobile block below CD, then the frictional resistance on CD may be incompetent to restrain the



FIGURE 5.—*Diagrammatic Representation of a Thrust Block, showing Failure due to underthrusting*

AB, surface of the earth; CD, thrust plane.

movement of the lower block, and the relative displacement may be indefinite in amount, without imbrication or other breaking up of the lower block.

The stress transmitted, however, to the upper block by reason of friction on CD may generate a strain in that block which will exceed the strength of the rock, and secondary ruptures will then be developed in it. This stress will not be applied to the cross-section of the upper block, but to its lower part, and will have a non-uniform distribution in the cross-section. Under these conditions the strain in the upper block near CD may exceed the strength of the rock in that region, while the strain at the surface may be less than the strength of the rocks near the surface. Thus the ruptures that relieve the strain may start at CD and be propagated upward. If this happen, which seems probable, then these ruptures, by reason of the progressive change in the direction of stress consequent on progressive relief of strain, would be concave downward or toward the

direction of stress. The geometric relation of these curved rupture planes to CD is such that any movement on them, affording temporary relief of compressive strain, would develop another strain, which could only be relieved by normal faulting. These curved ruptures would be limited, both as to their extent and the amount of movement on them, by the frictional resistance on their surfaces; and this limit might be reached before they intersect the surface, or, if CD be not too deep, they might actually intersect the surface. In the latter case, or in the former after exposure by erosion, we would have an imbricated structure in the upper block, but no large displacement on the planes of imbrication. The imbricating ruptures would be distinguished from those developed in a mobile upper block by the reversal of the curvature. In the common case, in which CD is inclined, some of these secondary ruptures might reach the surface, while others, originating at greater depth, might fail to do so.

Now, since it has been shown that the mobile lower block, by gravitative stress, may move past the upper passive block to an unlimited extent, it is apparent that the same stress would have been competent to develop the rupture CD with which, for the sake of simplicity of discussion, we started; for, if we imagine a portion of the earth's crust actuated by gravitative stress so distributed that it tends to move past and under a neighboring passive block, the tendency will result in shear when the stress exceeds the strength of the rocks. Prior to rupture in the shear zone the upper passive block would fail and develop an imbricated structure; but one of the ruptures thus developed, namely, that most nearly coincident with the shear zone, or the boundary between the mobile and passive regions, would be susceptible of extension, owing to the universality of the force below this zone and the incompetence of friction to restrain its operation. This extension of the shear rupture would constitute a fault-plane on which relative displacement might take place that would be unlimited by frictional resistance. It would be an apparent overthrust but a real underthrust.

The extension of the shear rupture would relieve progressively the strain in the mobile block, and the direction of stress in the portion in advance of the rupture would, therefore, progressively change; and, on the principle that the angle which the plane of rupture makes with the direction of stress tends to be approximately constant, the direction of the rupture would correspondingly change. The latter would consequently become curved with the concavity to the right, or toward the direction of stress. This curvature of the upper surface of the mobile block indicates that as it passed the upper passive block it would do so by

rotation on a horizontal axis deep in the earth's crust, as shown in the diagram, figure 6, in which AB is the surface of the earth, CD the rupture, and O the axis of rotation. The depth of O is determinable if the curvature of CD is known. As displacement proceeds, the vertical component of movement at D is small and the horizontal component large, while the reverse is true at C. The large vertical movement at C necessitates a transfer of mass by viscous flow from below the mobile block, past the lower end of the rupture CD, to the region to the left of C, and a consequent rise of the surface at A. If A be a region of vigorous degradation, this transfer of mass from the right of C to the left may be a manifestation of isostatic adjustment and may in itself induce the gravitative stress in the mobile block below CD which causes it to rotate.

3. The third possible application of stress to a lower mobile block moving past an upper passive block is by the operation of a viscous current

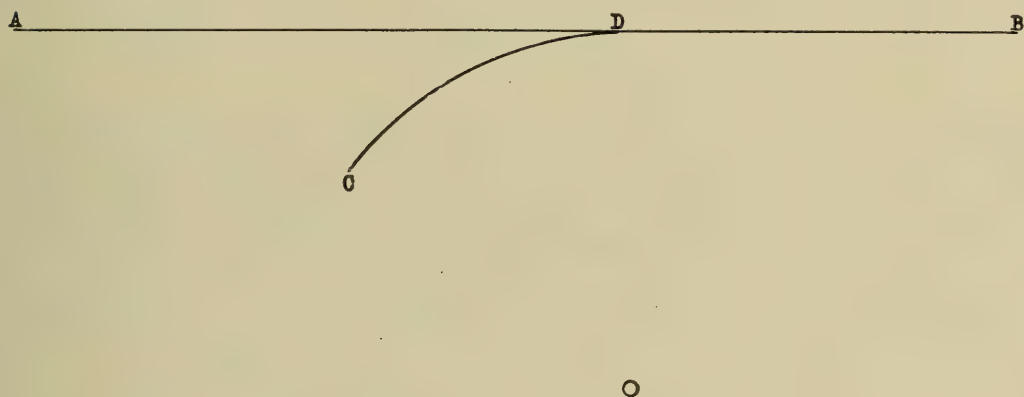


FIGURE 6.—*Diagram illustrating Thrusting by Rotation*
AB, surface of the earth; CD, curve thrust; O, axis of rotation.

below it. Here the stress would be applied to every point of the lower surface of the block and would be non-uniformly distributed in its cross-section. In the diagram, figure 7, let AB be the surface of the earth, CD an existent lowly inclined rupture, and MN the boundary between the rigid crust and an underlying viscous region. Let the current below MN be from right to left. The strain in the prism CDN M will be torsional, since the friction on CD is counter to the stress applied to MN. If the strength of the rocks in this prism be sufficient to withstand the tendency to rupture, and the current carry the prism with it, the latter will move on CD against friction and an imbricated structure, due to failure, will be developed in ABDC. The uniform application of stress at all points on MN makes this possibility not improbable. If, however, CDN M fail, the failure would occur in its lower part first because of the greater intensity of strain in that region relatively to strength. As a result of fail-

ure, innumerable shear ruptures would be formed and the rock would be caused to flow. This means that the boundary MN would be moved up and that the prism CDN would finally become thin enough to insure the transmission of a stress to all points on CD sufficient to overcome friction, when the lower block would move past the upper.

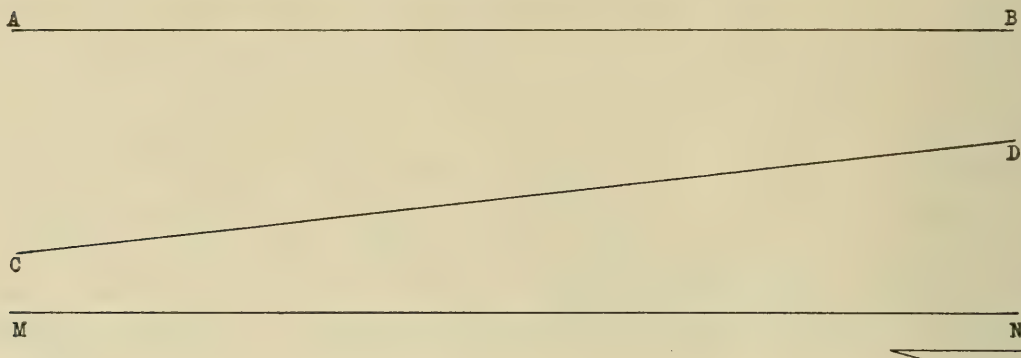


FIGURE 7.—*Diagram illustrating Thrusting by a Current moving from Right to Left below the Crust*

But if a deep viscous current be competent to cause displacement on CD against friction, it is also competent, for reasons previously advanced, to inaugurate and extend the rupture CD, and probably in this case the rupture would be started in depth and extended toward the surface, as in figure 8. With the initiation of the rupture, one of two things would happen. Either the mobile wedge would be driven under the passive

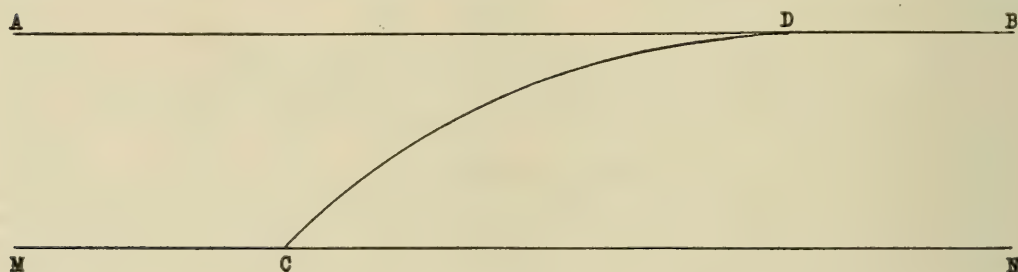


FIGURE 8.—*Diagram illustrating the Initiation of a curved Thrust, D, in Depth and its Propagation toward the Surface.*

block, causing its uplift, or the point of the wedge would be driven downward into the viscous current and be incorporated in the latter, also causing uplift beyond the intersection of the rupture with the top of the current. Inasmuch as the rupture would be concave to the right, it seems probable that the wedge would be forced down into the current, that a rotary motion of the mobile block would develop, and that the condition of transfer of mass would be analogous to those set forth in case 2.

COMPENSATORY FLOW AND UNDERTHRUSTING

Let ABC, figure 9, be an elevated land area in isostatic equilibrium with the area CD, the surface of which is at sealevel. Let the prism ABCE be transferred to CD by erosion. As a result of the disturbance of equilibrium, CD is depressed to CFD, and the mass of the prism CDF is equal to that of the prism ABCE, though the volumes may differ, owing to the less density of the newly laid sediments. The profile ABC is reduced and tends to assume the form EC. The profile EC is, however, never attained, owing to continuous compensation as the transfer of load proceeds. For purposes of discussion, we may assume that compensation, instead of proceeding *pari passu* with the transfer, begins after the latter

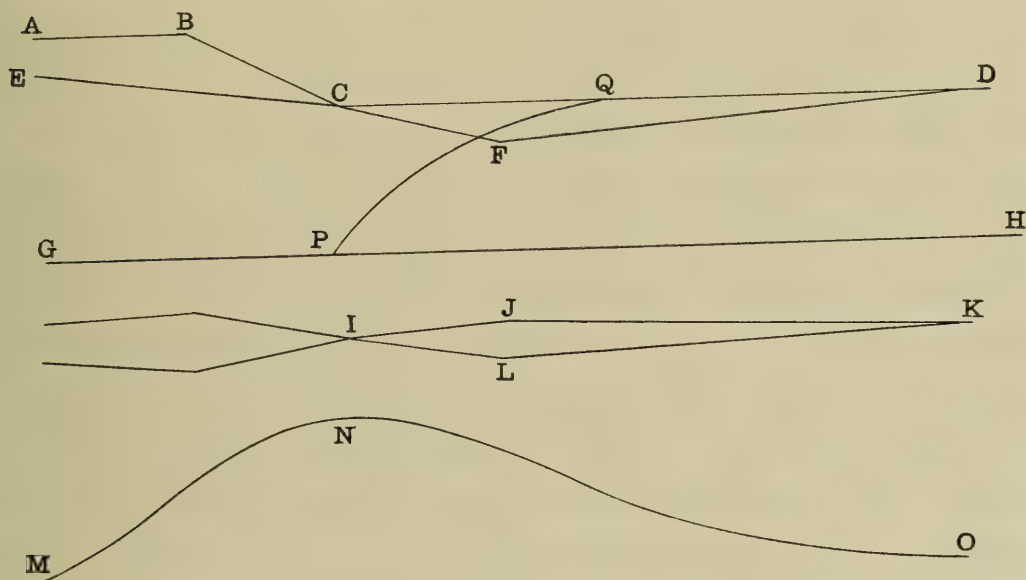


FIGURE 9.—Diagram illustrating the Development of the curved Thrust, PQ, as a Result of isostatic Compensation

has been completed, and that finally balance is restored, with no more residual than initial strain.

Compensation is effected by a deep transfer of a mass from the region under CD to the region under CE, and this mass is the same as that which has been moved from the left to the right of E at the surface. The deep transfer is effected by viscous flow of solid rock. The depth at which this transfer takes place is unknown, except that it probably lies within the limits of the zone of compensation, which may be taken at 75 miles. The viscosity doubtless diminishes with increasing temperature, and at some particular unknown temperature the curve of decreasing viscosity probably bends abruptly. Below the level marked by this temperature we

may, therefore, recognize a relatively viscous condition, in contrast to a rigid condition above. Let GH denote the boundary between the rigid and the viscous condition. Below GH a mass, represented by the prism IJKL,³ is transferred from the right to the left of CI. If this transfer be effected in a stream of uniform thickness, the flow of which begins throughout at the same time and ends at the same time, then the relative velocity of the latter is inversely proportional to the mass passing the points at which the velocity is compared. Under this assumption the relative velocity of the stream throughout the flow is indicated by the curve MNO, which is also the curve of the square root of the momentum of the moving mass. If the transfer is effected by a stream of unequal thickness, then the curve MNO still indicates the relative momentum of the moving mass, but not the velocity.

As appears in the diagram, figure 9, the maximum mechanical effect of the viscous stream is at the point I, or directly below C, the border line between relief and load in the transfer of mass by erosion. Whatever, then, may be the stress applied to the crust above GH by the viscous stream, that stress (that is, drag effect) would probably have its maximum in the region under C, and we should expect, therefore, the greatest strain and the first manifestation of underthrusting to be located to the left of CI; but, as has already been indicated, the stress would probably overtake the strength of the rocks at GH before doing so at the surface, and any rupture that occurred would be initiated at GH and be extended to the surface. Let PQ be such a rupture, on which underthrusting immediately proceeds. The mobile block to the right would be thrust under the passive block to the left either by wedging or by rotation. If by wedging, then partial compensation would result, and the viscous current, the cause of the thrust-stress, would be checked. If by rotation, partial compensation would be also effected by transfer of mass from right to left, and the urgency of the viscous stream would be similarly diminished; but if by rotation, which is the more probable, there is a more rapid relief of horizontal strain near the surface than near GH, since the horizontal component of motion on the curved rupture is large near the surface and small near GH. The strain set up in the passive block above PQ induced by frictional resistance on PQ would be relieved by (1) relatively short thrusts, with the development of an imbricated structure in the region below CF; (2) folding in the stratified rocks above CF; and (3) thrust-

³ The mass IJKL is less than the mass CDF by the amount which flows out to the right of D to compensate any disturbed balance in that direction, the amount which flows in from the left of E by reason of disturbed balance in that direction, and an amount corresponding to any residual strain.

ing of the same beds when they have become appressed and overturned. The region to the right of Q would remain unfolded.

The entire process would result in a typical folded belt in which the intensity of plication and thrusting is probably proportionate to amount of movement necessary to effect compensation; and this in turn is proportionate to the mass transferred by erosion from the left to the right of C; that is, the most profoundly plicated and faulted mountains are developed in regions of heaviest sedimentation, which is a fact well known to geologists.

It should be noted that the plication and thrusting can only proceed while the deep compensatory current is flowing, thereby furnishing the necessary stress; but so long as the current flows and underthrusting is effected by rotation on PQ, a portion of the light rigid crust under PQ is being pushed down into the heavier viscous subcrust, which, in so far as it is not removed by the current, induces elevation of the surface of the folded region by flotation. In this circumstance we have a probable explanation of the uplift of folded regions into mountain ranges. This elongation of the column under the folded belt necessitates, of course, a displacement of the viscous layer at its base, thereby inducing currents both to the right and the left of the folded region, the former eventually neutralizing the causal current of the whole complex condition of strain and so bringing the process to a close.

It is further to be noted that the loading of the region CD determines a tendency to uplift to the right of D as well as to the left of C, and that underthrust movement induced by the viscous current implies a tensile strain in the neighborhood of DH. Since, however, part of the mass that moves from under CD flows to the right of D, the maximum tension is probably located in depth between D and Q, and this condition may explain the development of a batholithic magma in that region.

WEIGHT OF SEDIMENTARY ROCKS PER UNIT VOLUME¹

BY ALFRED C. LANE

(Presented before the Society December 29, 1921)

CONTENTS

	Page
General importance of the data.....	353
General engineering data on porous and fragmental rocks.....	354
Methods of determining weight per unit volume.....	356
Work of Charles C. Moore.....	359
Data from drill cores.....	361
Data on friable material.....	362
New data from tests on glacial brick-clays.....	363
Comparative data on other clays.....	366
Applications to gravitative anomalies.....	367
Summary.....	369

GENERAL IMPORTANCE OF THE DATA

The importance of the study of the volume, composition, and weight of rocks was the theme of the presidential address of C. C. Moore² before the Liverpool Geological Society.

The specific weight of a rock, as ordinarily given in textbooks or determined by chemists, is not the weight of the rock, but the weight of the rock powder. In a rock there are always pores, which may be filled with air, gas, oil, or water, and thus it is only in the compact rocks, like granite, where the porosity is very low, that the two expressions, "sp. gr." and "weight of rock per unit volume," accompanying chemical analyses, are nearly equivalent, if the latter is given in tons (metric) per cubic meter. I use these units in tables, but in the text, to avoid decimals, I refer to thousands of ounces per cubic foot, assuming that a thousand ounces of pure water have the volume of one cubic foot. In such expressions the figures for weight per volume are directly comparable with specific grav-

¹ Manuscript received by the Secretary of the Society March 6, 1922.

This paper is one of a series composing a symposium on isostasy.

² Proceedings, vol. ix, part 1, pp. 129 et seq.; part 3, p. 247. See, also, February, 1898.

ity, while it is not hard to turn them into the commoner form, in English engineering books, of pounds per cubic foot, by dividing by 16.

Beside the pores, Becker has remarked³ that an appreciable volume may be cracks. Yet there are many practical and theoretical problems in which it is the volume of the rock and the proportions per unit of volume that we should know. It may be the practical question of how much there is in a given vein. It may be the theoretical one of the rate of growth of a delta at the mouth of a river bearing a certain weight of sediment to the sea each year. In particular we have the question, important in discussion of isostasy, as to what weight and attraction there may be in a certain thickness of rock.

GENERAL ENGINEERING DATA ON POROUS AND FRAGMENTAL ROCKS

We find some data in engineering handbooks like Trautwine, Peele's Mining Engineer's Handbook,⁴ Lefax, Macdonald, etcetera. Warren J. Mead has also an article in Economic Geology, volume III, number 4, 1908, with an abstract in Lefax, sheet 7-355.

If a sedimentary rock is considered as a fragmental rock or elastic rock—an igneous rock all broken to pieces—we find that we may expect an increase of volume in the pile of pieces of about 50 per cent—that is, a porosity of 33 per cent and a decrease in weight per volume to about two-thirds. If its original weight was 2.7 tons per cubic meter, 2,700 ounces per cubic foot, its weight dry would be about 1,800 ounces per cubic foot, or 2,200 ounces if filled with water.

A. B. Macdonald gives, reducing to ounces per cubic foot:

	In place.	Broken.
Trap	2,992	1,712
Granite	2,720	1,552
Sandstone	2,416	1,376
Earth and clay, 50 per cent more than undisturbed.		

It is important in molding sands to have a high porosity to let the gases escape, and, as Ries⁵ and Rosen's figures show, they approached Moore's theoretical maximum—that is, 34 tests of molding sands give:

	Gm	Porosity.	Weight in tons per cubic meter.	
			Wet.	Dry.
Average	2.63	41	1.96	1.55
Maximum	2.73	45.9	....	....
Minimum	2.54	28	....	....

³ G. F. Becker: Proceedings of the Wash. Acad. of Sci., vol. vii, 1905, pp. 274-275. See, also, his note in the journal of the same academy, vol. iv, September 19, 1914, pp. 429-443.

⁴ Robert Peele. Wiley & Sons, 1918.

Ries and Rosen⁵ cite a crushed quartz rock used for molding sand which, with a specific gravity of 2.52, has a porosity of 30.6, which would mean 1,770 ounces per cubic foot.

From Trautwine we find that a cubic yard will swell to 1.75 cubic yards when broken in fragments, and that anthracite, which weighs something like 1,500 ounces to a cubic foot solid, will run to something like 800 to 1,000 ounces to a cubic foot in our cellar. Dry potters' clay will be something like 1,800 to 2,100 ounces per cubic foot. Sand will be something like 1,440 to 1,700 ounces per cubic foot. The more evenly sized it is, the lower will be the weight. With sea sand, even with thorough settling, there were 32 per cent of voids and the weight was 1,792 ounces per cubic foot. Wet sand, however, will weigh 1,856 to 2,064 ounces per cubic foot.

Peele's Handbook reports, page 119, that clay settling in water had 50 to 79 per cent of voids; that pebbles had 44 per cent of voids when loose and 39 per cent when watered and rammed. Dry sand weighed 1,600; wet, 1,952; dry gravel, 1,793; wet, 2,000 ounces per cubic foot. Dry clay might be as light as 1,020 ounces per cubic foot when loose, but 1,857 in place, or 2,082 if compressed. In hard broken rock voids were 35 per cent when all sizes were mixed and shaken, but *if screened to even size* voids rose to 45 to 48 per cent, and, generally speaking, 1 cubic yard cut corresponds to 1.4 cubic yards filled.

A. G. Webster⁶ found that a sand which, when screened, gave between the sizes below (*a*) the percentages below (*b*), showed no excess of water when mixed with 25.9 per cent (3.5 pounds of water to one of sand), but a slight excess with 3.75 pounds—that is, 27.3 per cent.

(<i>a</i>)	.2 to .073,	— to .034,	— to .022,	— to .011,	— to .0055,	— to .0029 inch
(<i>b</i>)	.05	.1	.4	4.85	55.05	22.25

are the percentages retained between these diameters—that is, more than half between .011 and .0055 inch. With the excess water the angle of repose was 14°.5.

Henry Mace Payne, in discussing Yukon mining,⁷ reports the weights of certain frozen material: Black and sandy muck, 1,401 ounces a cubic foot; gravel and sand rock, 2,189 ounces a cubic foot; bedrock, 2,590 ounces a cubic foot.

A. F. Melcher,⁹ using the paraffin dip method on oil "sands," as cited below, has given many observations on their porosity and mineral specific

⁵ Michigan Geological Survey, 1907, p. 52.

⁶ Proc. Nat. Acad. Sci., July, 1919, p. 263.

⁷ Transactions Canadian Mining Institute, vol. xvi, 1913, p. 236.

gravity, from which the volume weight can be calculated. It was, however, pointed out in the discussion that the lumps he used, being less friable, were probably more cemented and less porous than the average.

Yet while the mineral specific gravity was almost invariably between 2.6 and 2.7, the pore space ran as high as 37.7 per cent for the Tertiary sands of Mexico and 36.7 for those of Louisiana. The Paleozoic sands of Pennsylvania were naturally less porous, 18 per cent being near the maximum porosity. This would mean 1,800 ounces and 2,200 ounces per cubic foot respectively.

METHODS OF DETERMINING WEIGHT PER UNIT VOLUME

The weight per unit volume may be determined from the specific weight of the rock substance and the porosity. This is, however, rather cumbersome, and it seemed well to have more direct and authentic ways of measuring this weight, which, while less accurate, perhaps, in some cases were simpler, more rapid, and more authentic in others.

There are three ways in which I have done this:

1. In the first place, I have taken cylinders and measured their volume and weighed them. This is the method which was successfully used by Sidney Powers and myself⁸ in tracing the variation in weight due to magmatic differentiation in a series of diamond-drill cores from a 500-foot trap sheet. For hard rocks samples have been diamond-drill cores, but with an instrument like Davis's peat sampler it is quite possible to take short cylinders of clay and to measure their volume with an accuracy near 1 per cent.

2. A second method is to cut out bricks, though I find that to get sharp forms they have to be rubbed down to a smooth surface, perhaps on sandpaper or a file.

3. A third method, which I have recently used at the hint of A. F. Melcher,⁹ is in some ways more convenient, is capable of greater accuracy, and is particularly applicable to friable material.

A mass of friable material, which should be cool, is dipped in paraffin just melted; a little unmelted piece floating about is desirable. This makes a solid mass, the weight of which in water can easily be obtained, and by simply taking the weight before dipping, after dipping, and in

⁸ Am. Inst. Min. Eng. Bulletin, 1916, pp. 534-548, 893; Transactions, vol. liv, 1917, p. 450.

⁹ A. F. Melcher: Determination of pore space. Transactions American Institute of Mining and Metallurgical Engineers, 1921, vol. lxxv, p. 470. Reference is made to Hirschwald's "Die Prüfung der Bausteine auf ihre Wetter beständigkeit" (Berlin, 1908, Ernst und Sohn), but I have not seen that. See also Rosenbusch Wülfing, "Mikroskopische Physiographie," vol. i, 1904, part 1, p. 46.

water, it is found that usable results may be had. For instance, let us adopt the following symbols, using Melcher's symbols and Mead's names as far as possible. Mead does not discriminate between the wet and the dried-out ore or the shrinkage in volume. This is small in ores, but may be 15 per cent in clays.

Let G_m = mineral specific gravity (usually 2.6 to 3.0)—that is, that which is obtained by pycnometer on the powder or by noting how many grams of powder it takes to add to a burette of water 1 centimeter in volume.

Let D = density of dry porous material, tons per cubic meter; also called W_v .

Let d refer to a dry sample;

w refer to a wet sample;

p refer to a sample coated with paraffin or to the coating;

s refer to a sample submerged in water.

For example, W_{wps} means the weight of a wet (saturated) sample coated with paraffin and submerged in water.

V_{wps} refers to the volume occupied by the same.

G is the weight per unit volume of the material as a whole.

$G_d = W_d / V_d$ and is $>$ than D of Mead, owing to shrinkage in drying.

$D = G_m (1 - P_w) = W_d / V_w$.

P_w = porosity of wet rock in place = $(W_w - W_d) / V_w$.

M = moisture of saturation expressed as a percentage of the wet weight = $P_w / G_w = P_w / (G_m (1 - P_w) + P_w)$.

M is in sediment usually about half of P_w .

Now we measure:

Illustrative Example

(1) W_w = weight of freshly taken or saturated sample 15.5

(2) $W_{(wp)}$ = weight coated with paraffin 16.4

(3) $W_{(wps)}$ = weight of paraffin-coated sample in water 7.3

Let $W_{wp} - W_w = W_p$ = the weight of paraffin .9

Assuming specific weight of paraffin to be .9, $W_p = .9 V_p$ and $V_p = 1$.

$W_{wp} - W_{wps} = V_{wp}$, which is 9.1

$G_w = W_w / V_w$
 $= W_w / V_{wp} - V_p$, thus subtracting 1.

$= W_w / W_{wp} - W_{wps} - 1 \div W_p$ 15.5 ÷ 8.1 = 1.92

taking $1 W_p$ and subtracting it from W_{wp} , we have

W_w and there is $0.1 W_p$ left—a small quantity;

whence we have, neglecting it, $15.5 / (15.5 - 7.3 = 8.2)$

$$G_w = W_w / W_w - W_{wps} (-0.1 W_p) = 1.89$$

correction for paraffin	.03
	1.92

The error incurred by neglecting the last term in the denominator is (if the weight of paraffin is not over one-tenth of the other weights) less than 1 per cent. It is the only term in which the specific weight of the paraffin comes in, so there is no great error there, and if we neglect the paraffin entirely and simply divide the weight by the loss of weight when dipped in paraffin and immersed in water, we make no great error if we keep the paraffin skin small.

Similarly we shall find, for the dry weight,

$$D = W_d / (W_w - W_{wps} - .1 W_p)$$

but

$$G_d = W_d / V_d$$

$$= W_d / W_d - W_{pds} - .1 W_p$$

and if the shrinkage S is 12 to 15 per cent¹⁰

$$V_d = (1 - S) V_w$$

$$(1 - S) G_d = D$$

We see that there is, as shown in Mead's diagrams, a connection between weight wet (G_w), porosity (P_w), per cent of moisture M , and mineral specific gravity G_m ; and if we assume G_d and D to be the same (as we probably may for coherent rocks), or if we have measured the shrinkage S in any way, they, too, are connected.

If we assume some definite value for the mineral specific gravity, as Mead calls it, (G_m)—for example, 2.8—then a simple straight-line diagram (figure 1) shows the connection between porosity and wet and dry weights, and the per cent of moisture is a hyperbolic curve.

4. The older method, that used by C. C. Moore,² depends on obtaining the mineral specific gravity and the porosity by measuring the moisture absorbed, and is thus described by him (page 134):

"The thoroughly dried rock specimen is kept *in vacuo* (about 29 inches mercury) for several hours, and then air-free water is slowly admitted into the evacuated vessel until the specimens are completely under water. Air is after-

¹⁰ H. Ries: Report on clay. Geol. Survey Mich., vol. viii., part 1, pp. 6 to 12. The 30 to 40 per cent on page 12 is by volume.

wards admitted, and the specimens left standing for several hours in the water at atmospheric pressure. When the pores are very small, it is advisable to leave standing 24 hours, as they fill very slowly."

A full discussion of refinements is given by Melcher.⁹

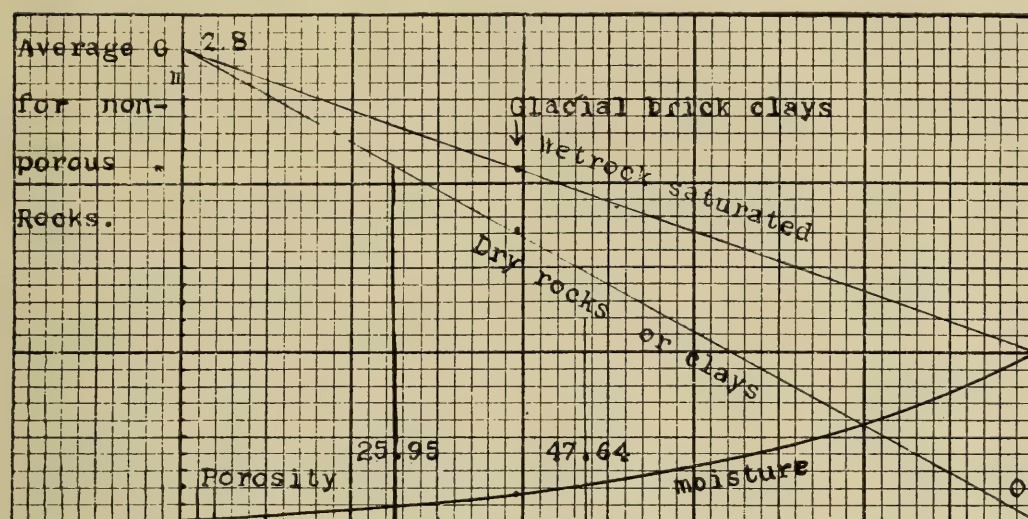


FIGURE 1.—Diagram showing by Ordinates the Weight in Tons per cubic Meters and Per cent of Moisture absorbable of Sediments of Porosity indicated by Abscissas

In this the customary range of porosity is assumed to be between 25.95 per cent and 47.64 per cent, as shown, and the specific gravity of the minerals is supposed to average 2.8. The average results for fresh taken glacial brick clay and the same dried are indicated by dots.

WORK OF CHARLES C. MOORE

The address of Moore above cited² gives the theoretical packing of spheres based on the well known work of Schlichter, in the Nineteenth Annual Report of the United States Geological Survey, and others, and he also gives 129 tests of the mineral specific gravity G_m and porosity, from which the volume weight can be figured. He discusses the increasing density of sandstone near a fault, of slate near a contact, of a sill near its center, and various iron ores, a subject which Mead has fully treated, bringing out points of interest to geologists.

The theoretical work may be condensed as follows (it being a composite of the results of Schlichter, Moore, Harker, and Reade):

A. Spheres all equal Size (a)

	Porosity, per cent.
1. Spheres arranged at corners of cubes.....	47.64
2. Closest hexagonal packing on horizontal, radius of sphere (a), vertical tiers directly over each other.....	39.54
3. Closest packing in two planes.....	30.18

(He calls attention to this as approached by many sandstones and as furnishing a more rapid flow in one direction, which is, of course, true in most natural sediments.)

4. Tetrahedral packing (no greater velocity in one direction than another), one sphere rests on three..... 25.95

B. *Spheres unequal Size*

5. Eight spheres on cube corners, size (a), one at center between them (size, $a\sqrt{3}-1$) (equal flow in three directions)..... 27.121
6. Tetrahedral packing as in group 4, with small spheres at center of tetrahedron ($.2245 a = a(\sqrt{6}-1)/2$), equal flow 24.28
7. Tetrahedral packing as in group 4, with small spheres whose centers are at center of tetrahedral faces, whose radii are $.414 a = a(\sqrt{2}-1)$ 20.67
8. Tetrahedral packing with both kinds of small spheres of 7 and 8.. 19.02

Of course, in nature this perfect condition is not reached, but in general it may be said that irregularity of shape will increase the porosity, and irregularity in size will generally decrease it, though *it may not if the proportions of the smaller grains are too near those of the larger.*

We see that the range of the theoretical figures is quite that of the practical figures given by Trautwine.

We summarize Moore's 129 tests, beginning with the lightest:

	Gm	Porosity.	Weight in tons per cubic meter.	
			Wet.	Dry.
Pumice	2.25	{ 64.1 63.63	....	....
Cave earth (Kent's tavern, Torquay) ..	2.67	21.23	....	....
Friable Eocene sandstone.....	2.61	33.8	2.18	1.86
Red Triassic "bunter" sandstone, about like Boston brownstone, highest.....	2.62	30.80	....	....
Average of seven not indurated pieces.	2.63	28.21	2.13	1.85
Hard layer.....	2.62	13.18	....	....
Layer condensed by fault.....	2.62	11.18	....	....
Permian Penrith sandstone.....	2.64	24.80	....	....
Average of tests on Permian and Trias	2.63	20.61	2.27	2.07
Millstone grit, coarse.....	2.63	18.20	....	....
Millstone grit, fine.....	2.64	13.01	....	....
Devonian Upper "Old Red".....	2.59	15.95	....	....
Cambrian Olenellus sandstone.....	2.61	6.13	....	....
African auriferous quartzite.....	2.66	1.91	....	....

Conglomerate and pebble beds do not differ much from sandstones, though with a less maximum.

	Gm	Porosity.	Weight in tons per cubic meter.	
			Wet.	Dry.
Most porous pebble bed given.....	2.62	28.52	....	....
Average of six, including one with barite and one with limonite infiltrations	2.64	22.61	2.28	2.05
<i>Calcareous Rocks:</i>				
Average of three chalks (maximum, 42.8 per cent).....	2.69	28.78	2.20	1.91
Average of five oolites (Jurassic).....	2.68	14.58	....	....
Carboniferous limestone, dolomitic....	2.82	9.44	....	....
Others have less weight and porosity and are probably cherty.				
Average of four Silurian limestones...	2.69	2.79	....	....

Argillaceous Rocks:

The highest porosity of a shale (they are all Paleozoic and many altered or black) is the Pusgill Silurian shale				
	2.72	10.00	....	....
Archean schist gives.....	2.74	2.32	....	....
Eight slates and schists.....	2.78	2.69	2.75	2.72

Igneous Rocks:

These run from the siliceous—for example:

Pumice	2.25	63.63	....	....
Arran pitchstone.....	2.35	0.09	....	....
Granite, cornwall, fresh.....	2.66	2.20	2.60	2.58
Granite, decomposed.....	....	19.90	....	....

To the basic—for example:

Hendre dolerite sill—				
From top.....	2.81	0.12	2.81	2.81
To center.....	2.91	0.64	2.90	2.89
Giant's Causeway basalt.....	2.89	0.79	2.88	2.87
Amphibolite	3.08	0.90	....	....
Serpentine of the Lizard, Cornwall....	2.59	5.90	....	....

DATA FROM DRILL CORES

If we compare these with results obtained by measuring and weighing drill cores, we see that, for the igneous rocks, they are quite comparable. A series of measurements showing the variations in one trap sheet are given by Powers and Lane¹¹ from 2.5 to 2.6 at the amygdaloid top to 2.97

¹¹ Trans. Am. Inst. of Mining Engineers, vol. liv, p. 442.

at the densest part, a little below the center, growing then less to the bottom. I add a few other drill-core results from Keewenawan rocks. It will be seen that the variation from Moore's results is less than 5 per cent.

Weight dry, in tons
per cubic meter.

Sedimentary:

Eastern sandstone, closely resembling Moore's		
Triassic sandstone, but older and deeper and		
near fault (Cambrian), Oneco.....	8.1270+	2.35
Oneco.....	8.1850	2.50
Oneco.....	8.715	2.62

Fine-grained Sediment:

Nonesuch shale, black, near lode and fault, with small vein.....	2.80
Arvon (Huronian) black slate.....	2.78

Igneous Rocks:

Porphyry with lithophysæ, Onondaga.....	8.700	2.42
Porous porphyry, Onondaga.....	7.177	2.60
Rhyolitic felsite, Onondaga.....	7.550	2.72
Quartz porphyry, Onondaga.....	8.894	2.41
Ophite, dense basalt like Causeway basalt or		
Hendre dolerite, Onondaga.....	4.141	2.91
Same as above, North Lake.....	3.110	2.93
Same as above, Oneco.....	9.660	2.96

DATA ON FRIABLE MATERIAL

It will be seen, however, that Moore's tests do not give much information regarding the friable shales and clays and the unconsolidated strata. It would be natural for them to be more porous, and hence lighter in tons per cubic meter than the more coherent rocks. The anomalies or variations in observed gravity from that computed¹² under the assumption of a 60-kilometer crust down to the level of hydrostatic pressure (the isostatic or asthenic layer) seem in regions known to me surely, and are probably generally, due to variations in the weight per cubic foot of the upper layers. It is important, then, to know what is the weight per cubic foot of the sedimentary rocks which are so often the outer layers. Deviations from this might mean extra light rocks filled with gas or gypsum, or also extra heavy intrusions of trap. As to the so-called "marls," really bog-limes, the limestone dough of fresh-water limestones, we get some information from the estimates of the Portland cement factories as to the amount required to make a barrel of cement.

For instance, from the Michigan report on marl¹³ we may calculate

¹² Bowie: Coast and Geodetic Survey papers, especially no. 40.

¹³ Michigan Geological Survey, vol. viii, part iii, pp. 167-8.

(assuming the specific gravity of the calcite to be 2.7) 1,185 ounces per cubic foot as a general estimate, while in particular cases of denser bog-lime we find it 1,373 to 1,760, and at Zukey Lake, not far from Ann Arbor, 1,630 ounces per cubic foot dry.

Two lumps from the "shell marl" furnished by Ward from Monroe County, New York, to Tufts College gave by the paraffin method 1,140 and 1,390 ounces respectively per cubic foot dry.

A specimen from the British Oligocene, one surface of which is covered with the little snail *Melania turritissima*, on a compact cream-colored base, from Hempstead, and presumably of the Bembridge marls under the Hempstead beds, as described in Geikie's Geology, fairly firm, gave 1,890 ounces dry and 2,200 ounces wet.

A dry impure peat gave 680 ounces, the clay beneath it 840 ounces per cubic foot, the same as the Rio Grande silt cited by E. Wesley Shaw.¹⁴

In the United States Water Supply Paper 234, page 81, it is estimated that dry river mud weighs from 800 to 2,000 ounces per cubic foot. As this involves shrinkage in drying, if the water were expelled by the generation of gas the rock might for a time be even lighter.

NEW DATA FROM TESTS ON GLACIAL BRICK-CLAYS

In view of the facts above cited, the difficulty of handling friable samples, the consequent scarcity of data regarding them, and the difficulty of distinguishing mineral specific gravity and volume weight in references, it seems quite possible that J. Barrell,¹⁵ who has been followed by Bowie, while he has nearly correct figures for the igneous rock, which may probably apply to crystallines generally, has not allowed enough for the porosity of other rocks, and hence has too high a weight for the average Cenozoic rock of probably nearly 20 per cent for the first mile or so of rocks, especially those above sea-bottom and relatively undisturbed.

It occurred to me that, to get a fair idea of what the average weight of recently formed sediments might be, glacial clays offered special advantages. Being not closely assorted, they might indeed be a little more closely packed than the average sediment, since close sorting tends to

¹⁴ Science, vol. 38, 1913, p. 554.

¹⁵ Journal of Geology, vol. 22, p. 219, gives the following figures:

	Gm	Porosity.	Weight with pores half full, tons per cubic meter.
Average igneous rock.....	2.89	0.2	2.8
Shale	2.69	8	2.51
Sandstone	2.67	15	2.35
Limestone	2.76	5	2.64
Cenozoic rocks.....		..	2.67

greater porosity. But, in the first place, they give a sample of material scraped over by the glacier, from a considerable surface, and are a rock flour which approaches close to the average rock, as estimated by Clarke, Daly, and Washington, as the analyses given below show. In the second place, they are firm enough, perhaps were even loaded down by ice, to hold their shape wet or dry long enough to be measured, either by volume or by paraffin dip. So I have had students and assistants help me in making repeated tests on the clay of the clay pits of the New England Brick Company of Medford, near the Wellington Bridge, and on Riverside Avenue, about one mile from Medford Square. They were also the subject of a graduation thesis by L. H. Carter in 1912. The pits are about 30 feet deep. Under 5 to 6 feet of outwash gravel comes a 10-foot layer of clay; then 1 to 2 feet of gravel; then another clay bed. Carter's analysis is of the lower bed.

MEDFORD BRICK-CLAY

L. H. Carter, Analyst

Average of Three Analyses

	With moisture.	Moisture-free.
Silica	57.60	60.7
Alumina	19.09	20.06
Ferric oxide.....	2.55	2.69
Ferrous oxide.....	4.20	4.40
Magnesia	5.19	3.26
Lime	2.12	2.24
Soda	1.40	1.5
Potash	4.60	4.86
Water	5.06	....
P ₂ O ₅	.40	.42
S	.16	.17
Titanium oxide, present with alumina, about 1 per cent.		
	100.36	100.30

Chlorine, S. A. Siegel, .047.

Average weight of same material as Mr. Carter analyzed, air-dried seven years (shrinkage cracked) = G_d , $1.71 \pm .013$.

Average weight of samples wet from the bank, upper stratum = G_w , $2.08 \pm .017$.

Samples taken in a series of distances in from the surface of the bank gave intermediate values from 1.74 to 1.9+.

Total water, one sample, 15.77 per cent.

Loss on ignition, 2.82 per cent.

There is marked shrinkage in drying, so that $D < G_d$ and is < 1.71 .

Thus porosity = $G_w - D > .37+$.

Whereas in the average sample tested the porosity would be if $G_m = 2.8$, not over .344.

In 1920-1921 A. J. Collins, for his thesis, made a study of clays from Blakeley's pits on Holyoke Street, Lynn—latitude, $42^{\circ} 28'$; longitude, $72^{\circ} 58.8'$ —about 500 yards from the Saugus River.

A and B were gray oxidized clays, respectively 4 and 10 feet below the surface.

C and D were blue, more plastic clays, respectively 4 and 13 feet below the surface.

The analyses were all computed water-free in this undried clay, direct from the pit, but the per cent of water was also determined. Moisture was determined in weighing tubes and ignition loss in a porcelain crucible.

Students' tests on samples, taken at the same time and of varying dryness, gave from 1.69 to 2.18 tons per cubic meter, with the best value 1.78.

Sample A

	A Per cent.	B Per cent.
Silica	60.79	60.74
Ferric oxide.....	5.11	5.14
Ferrous oxide.....	1.42	1.41
Alumina	17.78	17.73
Titanium oxide.....	1.	1.01
Lime	2.05	2.08
Magnesia	3.20	3.22
Soda	3.16	3.14
Potash	6.33	6.37
	100.84	100.84
Moisture		2.82
Ignition loss.....	4.27 to 4.19....	4.23
Per cent of H ₂ O in undried clay direct from pit.....		15.97

Sample B

	A Per cent.	B Per cent.
Silica	60.58	60.60
Ferric oxide.....	5.34	5.31
Ferrous oxide.....	1.88	1.87
Alumina	14.70	14.76
Titanium oxide.....	.96	.97
Lime	2.47	2.50
Magnesia	2.80	2.78
Soda	3.61	3.66
Potash	7.78	7.82
	100.12	100.27

Moisture	2.35
Ignition loss.....	3.51 to 3.61.... 3.56
Per cent of H ₂ O in undried clay direct from pit.....	24.61

Sample C

	A	B
	<i>Per cent.</i>	<i>Per cent.</i>
Silica	62.07	62.04
Ferric oxide.....	4.66	4.69
Ferrous oxide.....	2.40	2.42
Alumina	18.04	17.98
Titanium oxide.....	.96	.97
Lime	2.25	2.30
Magnesia	3.46	3.47
Soda	1.91	1.87
Potash	4.29	4.28
	100.04	100.02

Moisture	1.56
Ignition loss.....	3.37
Per cent of H ₂ O in undried clay direct from pit.....	18.47

Sample D

	A	B
	<i>Per cent.</i>	<i>Per cent.</i>
Silica	56.73	56.76
Ferric oxide.....	7.39	7.40
Ferrous oxide.....	3.40	3.42
Alumina	18.57	18.55
Titanium oxide.....	.90	.89
Lime	1.71	1.77
Magnesia	3.25	3.22
Soda	2.01	2.03
Potash	6.06	6.03
	100.02	100.07

Moisture	1.61
Ignition loss.....	4.38
Per cent of H ₂ O in undried clay direct from pit.....	19.68

COMPARATIVE DATA ON OTHER CLAYS

A series of residual clays given me by Dr. E. S. Moore, of Pennsylvania State College, gave comparable results as follows:

Moore's description.		Weight, dry, in tons per cubic meter.	
1.	Black River limestone, residual clay.....	1.766	.024 10 students' tests
2.	Upper Cambrian, Galesbury residual clay..	1.72	2
3.	} Various stream clays in a limestone country, number 5 not tested	1.82	2
4.		1.50	2
5.			
6.		1.78	7
7.	Stony wash from the Readville shale.....	1.97	6
8.	Juniata clay.....	1.93	5
		1.82	34 tests

APPLICATIONS TO GRAVITATIVE ANOMALIES

The diagram (figure 1) shows the connection between the weight per cubic volume wet and the weight per cubic volume dry, or with the pores filled with gas, assuming no shrinkage and assuming the weight of the rock substance 2.8. It is easy to see how it can be modified to suit other specific gravities of rock substances, and easy to see, also, that one may expect to find, for sediments which are not too coarsely packed and compressed, a weight about $2/7$ to $4/7$ that of the mineral substance, not far from two tons per cubic meter. This will be less if the pores are filled with gas, and it is not inconceivable that oil and gas might be detected by an anomaly of negative character—that is, an abnormally low attraction of gravity above. G. F. Becker¹⁶ thought he noted some parallelism between magnetic anomalies and oil. The anomalies due to oil and gas would, however, be slight.

It has been suggested that the abnormally low effect of gravity on the coastal plain of the United States and in the Ganges Valley in India was due to a lightness of the recent sediment which had not been fully allowed for. Let us go into this a little.

The force of gravity at various stations is not observed to be exactly that which would be due to the attraction of the mass of the earth as a rotating spheroid with the mass that it has. This is due, in part anyway, to the immediate effect of the attraction of the masses near by, just as we find the mass of the earth by finding the effect on a pendulum of a big lead ball near by.

Now Bowie and Hayford have compared the observed force of gravity with that obtained, first taking no account of the local masses, only of the elevation of the station from the center of the earth. This is equivalent to assuming that the elevations of landmasses are in their effect on gravity

¹⁶ U. S. Geol. Survey Bulletin 40.

balanced at the surface, or, as it is said, that the isostatic compensation is at 0 depth.

A second solution supposes that 60 kilometers below sealevel is a level such that everything beneath can be treated as concentrated at the earth's center, and that above every column, no matter how long or short, whether under plain or mountain or under the sea, has the same pressure; so that a longer column must differ from the standard column,—which for material above sealevel is supposed to have a volume weight of 2.67,—by a uniform amount. This would be the effect if all was floating on a fluid crust of this thickness.

The third solution supposes that this crust is 113 kilometers, 70 miles thick.

The fourth solution, Bouguer's, supposes that the earth is rigid; that the crust, we may say, is of infinite thickness, and that local masses above sealevel weigh 2.67 tons per cubic meter and attract accordingly.

They give a series of maps showing how the observed attractions compare with those which should be expected on the four various suppositions. They give the corrections also for other depths (42.6, 56.9, 85.3, 113.7, 127.9, 156.25, 184.6 kilometers depths). The solution for a crust 60 kilometers thick makes the differences between the real and the calculated gravity least, especially in flat regions and in the valleys of mountainous regions.

So far as pressure downward is concerned, however, it makes no difference with these columns whether they have a uniform weight or one unequally distributed, so long as the total weight is kept the same. If the top is extra light with sediment or water, it is quite possible that it is balanced by extra weight at the bottom; but a column of uniform weight, and one of light top and heavy bottom, that weighs the same below will not have the same attraction on the top so far as their effect on gravity at the station of observation is concerned.

Bowie has given on page 73 a table from which may be computed without much difficulty the kind of effect produced. The observed gravity tends to be less on the Cenozoic strata, where the stations are very likely underlaid with strata which begin with a weight from two tons per cubic meter down, and a couple of thousand feet of such light strata would account for the effect produced.

But we have also seen that strata with gas in them are 10 to 20 per cent lighter; and this may help to cause a set of differences characteristic of gas. In that case observations of isostatic anomalies might have value.

Bowie's suggestion that the cause of certain positive anomalies—that

is, excess of gravity—observed in certain small Precambrian areas, that the rocks near the surface weigh over 2,670 ounces per cubic feet, seems entirely pertinent.

My suggestion¹⁷ that the Lake Superior basin is in isostatic equilibrium, and that the Huron Mountain granite, with a weight of some 2,650 ounces per cubic foot, is balanced by some 20,000 feet of Keweenawan traps underlying Lake Superior, with a weight of 2,850 ounces per cubic foot, implies a deviation of gravity toward the lake which really seems to exist.¹⁸

SUMMARY

The mean weight of wet sedimentary rock probably varies from less than two tons per cubic meter, equivalent to 2,000 ounces per cubic foot, upward, as the water is squeezed out, and there is a good deal of connate water to be squeezed out, as Johnson has remarked. Glacial brick-clays may serve as a good average. Weighing a sample with its natural moisture, then dipping in paraffin and weighing again and when immersed in water, is a rapid way of making tests, which agrees with other methods. More data as to volume weights are desirable, although quite a number are assembled.

The suggestion is confirmed that the abnormally low gravity in the Coastal Plain of the United States and in the Ganges Valley in India is due to a lightness of the recent and upper sediment which has not been fully allowed for, and the suggestion is made that as gas- and oil-filled strata are yet lighter than water-filled, they also may be marked by anomalies of gravity.

¹⁷ Michigan Geological Survey, 1906, p. 485.

¹⁸ Plate 18, Coast and Geodetic Survey Publication 40.

RÔLE OF ISOSTATIC STRESS¹

BY BAILEY WILLIS

(Presented by title before the Society December 29, 1921)

CONTENTS

	Page
Gilbert's <i>versus</i> Hayford's concept of isostasy.....	371
Curve of isostatic stress.....	372
Incompetence of isostatic stress to produce motion in the lithosphere.....	372
Conclusion: Isostasy can not produce, but may direct, earth movements, whose cause is to be sought in the effects of the periodic activity of in- ternal heat.....	374

GILBERT'S VERSUS HAYFORD'S CONCEPT OF ISOSTASY

"Mountains, mountain ranges, and valleys equivalent to mountains exist generally in virtue of the rigidity of the earth's crust; continents, continental plateaus, and ocean basins exist in virtue of isostatic equilibrium in a crust heterogeneous as to density."—*G. K. Gilbert, 1890.*

The relation between rigidity and equilibrium in the lithosphere was thus stated by Gilbert thirty-odd years ago, and seems to me still to have been most philosophically and accurately stated. Opposed to this view, or rather supplementing it by refinements of extraordinary precision, is the conclusion reached by Hayford and Bowie, to the effect that complete isostatic compensation exists generally within the depth of 71 miles and for areas of a square degree of extent or even less. I have elsewhere² stated my reasons for not being able to accept the conclusions based on the mathematical analysis of gravity determinations, and will here only repeat that I question the assumption of distribution of density postulated by Hayford, and also the assumption of hydrostatic pressures at and below the level of compensation. If these two assumptions be erroneous, the mathematical structure built on them can not stand.

¹ Manuscript received by the Secretary of the Society April 3, 1922.

This paper is one of a series composing a symposium on isostasy.

² Bailey Willis: Discoidal structure of the lithosphere. *Bull. Geol. Soc. Am.*, vol. 31, 1920, pp. 266-269.

In spite of this disagreement with my colleagues as to the degree of isostatic compensation which may actually exist, I recognize that there is an isostatic stress which is set up by erosion and deposition or by eruption of basic lavas. It will suffice in this brief statement to consider only erosion and deposition. The question which I propose to discuss relates to the competency of that stress to cause movement in the lithosphere, or possibly only to direct movements which arise from other causes.

CURVE OF ISOSTATIC STRESS

It may be agreed that the lithosphere, at least that part of it which lies within the zone of compensation, is highly elastic, like a musical string, and responds readily to changes of pressure or temperature, *but within elastic limits*. If so, the effect of erosion in unloading a mountain region must be similar to that produced by taking weights off a spring balance; and, similarly, the effect of loading by the deposition of sediment in a depressed basin must be like that produced by placing weights on a spring. When these two effects occur in adjacent parts of a continuous mass, the downward stress in the one will be linked with the upward stress in the other in such a way that there will be a tendency for movement to take place from the loaded toward the unloaded section. The lines of continuous stress will thus form a curve, which will extend downward to a certain depth in the loaded section and thence proceed horizontally or diagonally upward toward the unloaded section, approaching the surface in a steeply inclined or vertical direction. The curve thus formed may be called the curve of isostatic elastic stress.

Now if the isostatic elastic stress be adequate to cause movement, there will be a flow of material from the loaded to the unloaded section, and inasmuch as the stress originates in the unloaded section, the flow would be in the nature of an undertow. This is the movement postulated by Hayford, who, in that concept, follows the original idea of Dutton. On the other hand, if the isostatic stress remain within the elastic limit, it will not cause movement. Nevertheless, it may direct molecular displacements due to other causes.

INCOMPETENCE OF ISOSTATIC STRESS TO PRODUCE MOTION IN THE LITHOSPHERE

Since Adams has shown that the strength of rocks increases notably under pressure, and that the lithosphere is therefore much stronger than we were wont to consider it, the comparative weakness of isostatic stress has become very evident. According to Adams's experiments, the rocks

at a depth of 5.8 miles below the surface have so gained in strength, because of confining pressure, that they are competent to support a column of rock 23.3 miles high; that is, they are four times as strong as the load which rests on them, and, even though the weight of a mountain range two or three miles high were added or subtracted, there would be no movement in the rigid foundation, except an elastic one. While it is admitted that a sufficient rise of temperature lowers the internal friction of rocks until they may even become liquid, it can not be assumed that that condition is originated except at depths exceeding 30 miles, and even there only as an occasional and not as a permanent condition. Thus the outer portion of the lithosphere must be regarded as a very rigid and adequate foundation for all the minor irregularities of the earth's surface of the dimensions of mountain ranges.

Hayford answers this argument by an appeal to the slow yielding of substances under even very moderate stress, provided the stress be continued long enough. He appeals to geologic time, and certainly no geologist is likely to dispute his claim that there is enough of it. Nevertheless, the facts of geology do not accord with his argument, for it can be shown that the earth's surface has been stable during very long periods, whereas instability is characteristic of relatively short epochs. This is the reverse of what should be the character of the movements if slow yielding to fatigue were the manner of deformation.

To illustrate: Becker suspended long steel tapes in the Washington Monument and subjected them to strain by attaching weights which were far within the elastic limit. There was an immediate elongation, which represented the elastic stretch of the tapes. Then, during months, the tapes continued to elongate and took a set—that is to say, they did not recover when the weights were removed. The nature of this deformation was a slow, continuous yielding, involving a molecular readjustment that might be designated by the word *flow*. It was in no sense paroxysmal, nor did the elongation due to fatigue take place only during a brief episode after a prolonged period of immobility.

Earth movements, in contrast to those of the steel tapes, are markedly concentrated in brief epochs. For instance, we speak of the elevation of the Appalachian Mountains at the close of the Paleozoic as the "Appalachian Revolution." The phrase indicates the very great development of activity in mountain growth which followed the long period of stability that had endured during the Carboniferous. Similarly, the Jurassic, Cretaceous, and Eocene were, for our Atlantic coast, periods of extraordinary stability, during which the land was reduced to a very low peneplain; yet in the Miocene and subsequent epochs down to the present

there has ensued a decided uplift. The evidence of geologic history thus testifies definitely to the fact that the earth's crust is characteristically stable when lands are being reduced by erosion to a low grade plane, and when, therefore, the isostatic stress is approaching a maximum. And yet, that characteristic stability is interrupted by episodes of mountain growth which result in reducing the isostatic strain to a minimum. These relations of stability and instability are clearly not those which would result from the slow yielding of the lithosphere in consequence of fatigue induced by a small stress within the elastic limit.

CONCLUSION: ISOSTASY CAN NOT PRODUCE, BUT MAY DIRECT, EARTH
MOVEMENTS, WHOSE CAUSE IS TO BE SOUGHT IN THE EFFECTS
OF THE PERIODIC ACTIVITY OF INTERNAL HEAT

I conclude, then, that the isostatic stress is incompetent to produce deformation in the lithosphere, in so far as that deformation requires a force in excess of the elastic limit; and, further, that the appeal to time, as a factor which may enable a stress within the elastic limit to do the work, fails because the work done is not of the character which would result from fatigue of materials. Nevertheless, I recognize that there is a definite isostatic stress which affects those zones of the lithosphere in which erosion and deposition modify the equilibrium toward which large masses of unlike density tend. This stress is unquestionably related to the movements involved in continental uplift and mountain growth. It is oriented in the direction in which the movements take place, and its rôle is, in my judgment, to direct the movements which it is incompetent to produce.

The views which I have thus expressed have troubled for many years my speculations on the nature of the forces which produce earth movement. I would like to have believed with Dutton, and later with Hayford, that isostasy was competent to cause that undertow which seems to be implied by erosion and uplift; but the facts are too strongly opposed to that view. They call for the action of a far greater force, characterized by periodic activity. That force I believe to be the internal heat of the earth, alternately accumulated in and carried away from the asthenosphere, as postulated by Chamberlin and Barrell. The transformation of the heat energy into the mechanical energy which displaces mountains is brought about by molecular changes in the rocks, resulting in recrystallization and elongation in the direction in which the isostatic stress is oriented.

Thus isostasy is the rudder, not the motive power, of deformation.

ISOSTASY AND ROCK DENSITY¹

BY HENRY S. WASHINGTON

(Presented before the Society December 29, 1921)

CONTENTS

	Page
Summary.....	375
Introduction.....	376
Comagmatic regions.....	378
The normative average density.....	381
Discussion of the methods.....	381
The average rock.....	382
Method of calculation.....	383
Results.....	387
Normative densities and altitudes.....	391
The physical average density.....	399
The isopiestic level.....	402
Comagmatic regions and gravity anomalies.....	409

SUMMARY

In the present paper, which is an expansion of part of a former one,² there is presented a study of the relations between the average densities of different areas of igneous rocks and their average altitudes, with the object of correlating these relations with the theory of isostasy. The outcome of the discussion is that the general relation holds good: *the average density of the igneous rocks of a region varies in the opposite sense as the average altitude*. The results of the study, therefore, harmonize with and corroborate the theory of isostasy.

Comagmatic regions, in which the igneous rocks are shown by their similar chemical and mineral characters to be derived from the same magma, are briefly discussed, especially as to their bearing on isostasy, and the distribution of comagmatic regions throughout the United States is described.

¹ Manuscript received by the Secretary of the Society February 11, 1922.

This paper is one of a series composing a symposium on isostasy. Seven hundred copies of this article were reprinted for distribution by the Geophysical Laboratory and bear its imprint and the designation "No. 460."

² H. S. Washington: The chemistry of the earth's crust. Jour. Franklin Inst., vol. 190, 1920, pp. 794-814.

The normative method for arriving at the average density of a region is described in detail. This method consists in calculating the norm of the average rock of the region and, from the known densities of the normative minerals, calculating the average density. The average densities of many areas over the globe, including the earth as a whole, the continents and ocean floors, and many countries and States, resulting from these calculations, are given in Table III, and their relations to the corresponding altitudes are discussed.

The physical method of calculating the average density, which consists in averaging the specific gravities determined by the balance, is discussed and some results are given. It is shown that this method is not capable of yielding such consistent and reliable results for the present purpose as the normative method.

The depth of the "isopiestic level," or "depth of compensation," at which all the various columns of inversely varying densities and heights balance each other or exert the same pressure, is discussed. The depth is calculated from the known average altitudes and from the average densities calculated by the normative method, using different sets of areas. It is shown that the normative method is capable of yielding reliable results with proper data, and that the most probable value on this basis for the isopiestic depth is 59 kilometers, which agrees well with Bowie's value of 60 kilometers, arrived at by gravity methods at stations distributed over the United States, but which differs from that of 96 kilometers derived from mountain stations and accepted by Bowie as the best. It is shown that the former value is probably the more correct.

The correspondence between the distribution of comagmatic regions and areas of positive and negative gravity anomalies in the United States is briefly discussed.

INTRODUCTION

According to the theory of isostasy, the outer part of the earth, the "crust," is in a condition of more or less perfectly balanced equilibrium, and tends to act as if it were made up of columns of different densities, in the sense that, speaking generally, the higher the topography the lighter the material beneath it, and the lower the surface relief the denser the underlying matter. The crust is thus assumed to be made up, as it were, of long-light and short-heavy columns, which balance each other; so that it is upheld, not by the principle of the arch, but by what may be called flotation, although the material beneath is solid, or essentially so.

Observations with the pendulum and the plumb-bob have shown long ago that in many cases the lower the altitude the greater the force of

gravity, after correcting for latitude and elevation, and the converse; and it has long been recognized that the material underlying the ocean floors is much denser than that which underlies the continental masses. Isostasy therefore demands that the crust be non-homogeneous; in other words, the material beneath the various surficial areas of different altitudes must vary in chemical and mineralogical composition; for only thus can we explain the differences in density demanded by the theory and by the gravity measurements. It is true that the material beneath an area of high relief, such as a mountain range or a high plateau, is under greater pressure than that which underlies an ocean floor. But, if we could assume the same kind of rock in each case, the change in density brought about by the differing pressures is not only opposite in direction to that demanded by observation and theory, but is of an order of magnitude far too small to be appreciable, as we know from studies on the compressibility of rocks.³ Similarly, rise or fall of the isogeotherms, which would also bring about differences in density, would likewise be inadequate to produce differences in density which would correspond with what have been observed.

The earth's crust is composed of igneous rocks to the extent of about 95 per cent if it is assumed to be 10 miles thick, according to Clarke's⁴ estimate, or about 97.5 if it is 20 miles thick. The metamorphic rocks, gneisses and schists, are reckoned in with those of igneous origin, while the remaining 5 or, respectively, 2.5 per cent of sedimentary rocks (shales, sandstones, and limestones) form a very thin veneer on the surface. In dealing with a crust of such a thickness as is involved in the idea of isostasy and the depth of the "zone of compensation," therefore, we are justified in assuming it to be wholly of igneous rock. Now, study of the igneous rocks of the earth, of which about 10 miles or so in depth are accessible to our observation, shows that the chemical and mineral heterogeneity demanded by the theory of isostasy to account for the varying densities does actually exist; furthermore, that the differences in composition are of the order of magnitude to meet the needs of isostasy and are uniformly in the right direction.

It is the object of the present paper to discuss the bearing of petrology on the problem of isostasy; to explain briefly the petrological heterogeneity, both qualitative and quantitative, involved in the notion of comagmatic regions; to describe a method for calculating the areal densities

³ Dr. L. H. Adams has kindly calculated that, assuming at sealevel a non-porous granodiorite of density 2.80 and compressibility $\beta = 1.9 \times 10^{-6}$ per megabar, the density at a depth of 60 kilometers (the isopiestic level) would be 2.889.

⁴ F. W. Clarke: Data of geochemistry. U. S. Geol. Survey Bull. 695, 1920, p. 33.

from these data; and, finally, to correlate the results so obtained with the surface relief, and to compare these results with those derived from pendulum observations, as to both the surface relief and the depth of the so-called "zone of compensation."

COMAGMATIC REGIONS

For some fifty years it has been recognized that the igneous rocks of large areas show similarities in their chemical and mineral characters, which indicate their derivation from a common magmatic source, and which serve either to distinguish them from the rocks of other regions or to bring out the similarity between them and others. This idea of the existence of areas of related rocks is embodied in the terms "consanguinity" of Iddings, "petrographical provinces" of Judd, and the more recent "comagmatic regions," a term suggested by me as expressing better than the others the idea of derivation from a common magma. The existence of comagmatic regions and the apparently intimate relations between them and isostatic adjustment would seem to have been overlooked by geodesists and geologists alike.

The characters which may be regarded as peculiar to any given region, and which serve to distinguish it from others, are, as yet, somewhat vague. They are undoubtedly complex and are to be looked for in the ensemble of the general characters of the rocks of a region, rather than as manifested in any one rock. The most obvious comagmatic characters are mineral—shown, for example, by the peculiar color of the pyroxenes or amphiboles, the twinned structure of the feldspars, or the common occurrence in the region of minerals elsewhere very unusual. All such mineral characters, however, are ultimately dependent on the chemical characters of the magma or of the rock, so that the chemical characters are those which are the most truly distinctive of a comagmatic region. These chemical characters may manifest themselves in several ways. Thus, the rocks of a region may be marked by the uniform presence of unusually large amounts of one or more chemical constituents, as soda in the Christiania region, potash and lime in the Roman region of western Italy, potash and soda in that of Montana, iron oxides in that around Lake Superior, or lime and magnesia in the Urals.

Again, comagmatic regions with essentially the same characters may exist in widely separated parts of the earth, as in the Andes, the Balkan Peninsula, and the Rocky Mountains. The characteristics and the differences are manifold, few regions have been submitted to systematic study along these lines, and the technical details involved in a full discussion would carry us outside the scope of this paper.

The idea of petrographic provinces or comagmatic regions originally denoted a comparatively small area, but we are coming to consider as comagmatic the rocks of areas which may cover hundreds of thousands of square miles. As we shall see, even such areas of the first magnitude as the continental masses or the ocean floors may, in a sense, be regarded as different comagmatic regions. The factors of shape of the area and the geologic time of intrusion or extrusion of the igneous rocks must also be taken into account, but we must leave aside such details here.

For the student of isostasy the chief interest of comagmatic regions lies, not in their chemical or petrographical features, but in the evidence that they afford of the crustal heterogeneity of the earth, both surficially and presumably for a considerable distance below the surface, and in the corroboration of the theory of isostasy which their study affords.

It will be well to give an illustration of the distribution of some comagmatic regions, with succinct statements of their chief characters. That chosen is the distribution of the larger and more important regions of the United States, which is of special importance to us here because the igneous rocks of this country are well known chemically, the gravity constants and anomalies are well known throughout the extent of the area, and we have fairly accurate estimates of the average elevations of the several regions. On later pages the correlation between these three factors will be pointed out, but for the present we shall note only the distribution and general sizes and shapes of the main comagmatic regions, with their chief chemical characters.

In the extreme eastern portion, running generally parallel with the Atlantic coastline, is a narrow belt which extends from New England and the Maritime Provinces, with some interruptions, along the Appalachian uplift into Georgia, and which may possibly be continued in the Ozark uplift. This Appalachian region (and the Ozarkian) is made up chiefly of granitic rocks, which are characteristically rather high in soda and lime. The later extensive sheets of Triassic basaltic rocks, which are rather high in iron oxides, may be connected genetically with the Appalachian region. Scattered along the general Appalachian trend, and mostly along its eastern slope, are numerous isolated and small occurrences of plutonic rocks which are characterized by their high content in soda. These small areas occur in Ontario, Quebec, New England, New Jersey, Virginia, North Carolina, Arkansas, and Texas, and there is little doubt that they are the surface manifestations of a sodic comagmatic region beneath, which may be connected with the Appalachian one. West of the Appalachian region, in the eastern Mississippi basin and extending into Pennsylvania and New York, are some small, isolated occurrences

of plutonic rocks that contain much olivine and biotite and which are characterized chemically chiefly by low silica and high magnesia and iron, with considerable potash. These appear to be the surficial extensions of a general body of magma which underlies the greater part of this area.

Farther north, occupying the Laurentian shield around Hudson Bay, is a large and chemically little known region, whose igneous rocks are apparently mostly granitic gneisses, with large intrusions of anorthosites in the southern part; so that high silica and high lime may be said to be characters of this Laurentian region. South of this, around Lake Superior, is an area of (chiefly) basaltic rocks, with some granites. A prominent character of this region, which may be called the Algonkian,⁵ is the high content in iron shown by the basaltic sheets and flows. In and near the Ozark uplift, in Missouri and Arkansas, are occurrences of granites, which have been little studied, but which seem to constitute a separate Ozarkian region, the general chemical characters of which resemble those of the Appalachian region, with which it may be connected.

As we go west the comagmatic relations become more complex, as do the geological structures, but we can distinguish some fairly well marked regions. The best defined of these, the Montanan, extends from within southern Saskatchewan, through central Montana, into Wyoming and, as small patches, probably into eastern Colorado. This region is characterized chiefly by its high alkalies, with about equal amounts of potash and soda, and a high percentage of baria as a minor feature. In the extreme northwest is the Oregonian region, with its vast basalt sheets in Oregon, Washington, and Idaho, which are notable for their high content in iron oxides (like the Algonkian region). Extensive rhyolite flows accompany the basalts, but the relations of the two are not yet fully understood. A large and complex comagmatic region occupies the great high plateau of Colorado, Utah, and Nevada, with portions of Idaho, Wyoming, Arizona, and New Mexico. It is probable that further study will enable us to subdivide this great area into several distinct regions or subregions; but, taken as a whole, the chief chemical feature of this area is its medium or average character, with rather high silica, soda, and lime, little potash and moderate iron and magnesia. Finally, along the Pacific coast there appears to be a narrow zone of distinctly sodic and rather highly silicic rocks.

From this brief survey of the chief comagmatic regions of the United States, two facts which have a bearing on isostasy are evident. In the first place, the igneous rocks (which constitute almost all of the upper

⁵ I am indebted to Dr. A. C. Lane for the suggestion of this name.

crust) show very great differences in areal (not merely local) chemical and petrographic characters. Some of the regions (as the Appalachian, Ozarkian, and Coloradan) are essentially granitic or granodioritic, others (as the Algonkian and Oregonian) are gabbroic or basaltic, while still others possess intermediate or divergent characters. In the second place, consideration shows that the topographic and chemico-mineralogic features of the several regions are, in general, interrelated. Areas of high relief, as Appalachia and Colorado-Utah, are made up mostly of granitic rocks, which are rocks of low density, while areas of low elevation, as the Algonkian and the Oregonian, are composed largely of heavy gabbroic or basaltic rocks.

This relationship of high topography with rocks whose chemical and mineral characters imply a low density, while the areas of low topography are associated with rocks which on chemico-mineralogic grounds must be heavy, is, as we have seen, exactly the relationship demanded by the theory of isostasy. We shall find that such interrelations are generally true, not only for the United States, but for all the regions of the earth whose igneous rocks and surface features are sufficiently well known to permit of correlation. It remains now to render our ideas more precise and to place the correlation on as exact a quantitative basis as may be possible, at the same time extending our study to all possible regions of the earth. For this purpose we must arrive at a method of determining the average density of the igneous rocks of the various areas or regions, so that we may compare them with their average elevation above sealevel.

THE NORMATIVE AVERAGE DENSITY

DISCUSSION OF THE METHODS

Two methods are available for estimating the average density of the igneous rocks of a region. The one is chemico-mineralogical, and consists in obtaining first the average chemical composition of the igneous rocks of the region, calculating from this the corresponding (average) mineral composition according to a uniform method, so that the data for different regions may be comparable with one another, and from these mineral compositions calculating the average density, the densities of the several constituent minerals being known. This method, which was first used by Iddings, is here called the "normative method," because it makes use of the so-called norm of the quantitative system of classification of rocks as the mineral basis of comparison. The second method consists in averaging all available densities as determined on the actual rocks of a given region by the ordinary physical methods, as by weighing the speci-

men in air and water. This may be called the physical method. We shall discuss the normative method first and at greater length, because it is the more novel and, which is of more importance, it appears to lead to more reliable and mutually consistent results than the other.

THE AVERAGE ROCK

As a fundamental basis for the normative method we must obtain a knowledge of the chemical composition of the average igneous rock of the area, whether it be a small district, State, country, continent, or the whole earth. These average compositions have been arrived at by averaging the figures presented in a collection of chemical analyses of igneous rocks published between 1883 and 1913, inclusive.⁶ This covers all the petrologically known parts of the earth's surface, and includes over 8,000 analyses of varying degrees of merit. These were divided into two groups according to their quality—the superior analyses, which were considered to be satisfactory as to accuracy and completeness, and therefore reliable and sufficiently good for use, and the inferior analyses, which are either so incomplete or so inaccurately made, or both, that they are excluded from consideration for the present purpose.

For making the averages, 5,159 superior analyses were used, those of separate districts, States, or countries being averaged separately, and the results were combined into averages for larger areas, continents, and ocean floors,⁷ and finally for the whole earth. The greater part of this laborious series of computations was carried out by Dr. F. W. Clarke, to whom I am deeply indebted for his invaluable cooperation. Some supplementary averages have also been computed by me. All these averages, numbering about 50, are to be given and discussed at length in a forthcoming professional paper of the United States Geological Survey, under the joint authorship of Dr. Clarke and me. Some of them, which are best illustrative of the relations of rock density to isostasy, are presented here, and I have again to thank Dr. Clarke for kindly consenting to this prior publication.

Various objections have been and will be raised against averages obtained in this way. One is that the actual relative masses of the different kinds of rock are not properly taken into account, because there is an unduly large proportion of analyses of interesting and rare (therefore less generally abundant) kinds, while too few analyses are made of the

⁶ H. S. Washington: U. S. Geol. Survey Professional Paper no. 99, 1917.

⁷ The analyses of the rocks from the islands of the various oceanic basins were used to determine the averages for the ocean floors, as these lavas came up from magmas underlying the oceans, and they are the only means which we possess of obtaining the knowledge required.

more abundant, and therefore in general the less interesting, rocks. Another objection is that, in the case of many regions, the number of analyses is too few to be really representative; while a third one is that we can deal only with rocks near the surface and not with those at depths which place them beyond our reach, except through crustal movements. Each of these and other possible objections has some validity and is entitled to careful consideration, into which we can not enter here; they will be discussed in the professional paper referred to above. It may be said, however, in brief, that the force of these objections does not seem to be as great as is supposed by some. In any case, data such as these are the only ones available to us at present; so that we should make the best use of them which we can, without resorting to the very dubious procedure of applying so-called corrections, which are mostly based on personal opinions or estimates, and thus introduce quite uncertain subjective elements and very possibly errors of unknown magnitude, as to either extent or direction. The results presented here and in the future paper are thus to be regarded as a first approximation to a solution of the problem, admittedly tentative, but sufficiently accurate to permit us to judge of the direction and the order of magnitude of the differences.

METHOD OF CALCULATION

The average chemical composition of the area having been obtained from the analyses, it is recalculated to 100 per cent. It is best to retain the amounts of TiO_2 , P_2O_5 , and MnO , but the other minor constituents may be disregarded. The percentage amount of water ($\text{H}_2\text{O}+$) may be retained, following the plan of Iddings; but I prefer to calculate the densities on the basis of a water-free rock. My reasons for this, in brief, are: although water is present in the rock magma or lava and also in the original rock, yet the amount shown in the analysis can scarcely ever represent this accurately; in many rock specimens much of the water is present through alteration; lastly, but of great importance, much of the water ($\text{H}_2\text{O}+$) shown by the analysis does not exist as liquid water, but as "combined water" or as hydroxyl, and we have no means of knowing what density to assign to it. The density would certainly not be 1, almost certainly more than 1, and the reciprocal of such a small value has a very serious effect on the calculation of the density. I have, however, calculated all the densities on the two assumptions of a water-free rock (δ_a) and one which contains the water shown in the chemical average (δ_w). Both assumptions lead to the same results as regards the relation between density and altitude, as we shall see. The calculated densities for water-bearing rock are less than those for water-free rock; the loci and curves

are merely shifted up or down, but the relations remain practically unchanged.

The "norm" of the chemical average is then calculated according to the now well known methods employed in the quantitative system of classification of rocks.⁸ The chemical composition is thus reduced to terms of the mineral molecules which the chemical constituents present may, and in most cases do, form on solidification of the molten magma as a holocrystalline rock.

Several points of special importance are to be noted. In the first place, all rocks or rock averages are treated alike by a uniform method which does not admit of the influence of the personal equation; the results are thus mutually consistent, having been arrived at by identical means. In the next place, the mineral molecules to which the calculations lead are few and simple, and, which is of still greater importance, they differ among the various averages only in their relative amounts, and thus refer all the averages treated to the same conditions of pressure, rate of cooling, and other possible factors. Thus the same magma which on the surface would yield a mixture of leucite and sodic orthoclase would at depth, under intrusive conditions, yield a mixture of nephelite and purely potassic orthoclase, the two mixtures having different densities. Under the system here employed both would be referred to the same mixture (the second), differing only in the proportions of the constituents; so that the disturbing factor of qualitatively varying mineral composition is eliminated and their respective densities are strictly comparable *inter se*.

Again, and a point of very considerable importance, all differences due to texture, such as the presence or absence of glass, porosity or cracks, and other such features caused by different states of physical solidification, are wholly eliminated. Glass, when present, lowers the density of a rock, as do pore spaces; so that the presence of these would introduce a serious error, making the rock lighter than a dense holocrystalline rock of identical chemical composition. Inasmuch as we know that glass is not present at all, or at most in but insignificant amounts, in the deeply seated rocks, in which also the great pressures would tend to obliterate pore spaces, calculations based on the norm yield results which apply best to the rocks as they occur at great depth—that is, to the greater

⁸ Cf. Cross, Iddings, Pirsson, and Washington: Quant. Class. igneous rocks. Chicago, 1903, pp. 186-203.

Iddings: Igneous rocks, vol. i, 1909, pp. 433-444.

Finlay: Introduction to study of igneous rocks, 1913, pp. 149-192.

Washington: U. S. Geol. Survey Professional Paper no. 99, 1917, pp. 1162-1165.

portion of the rocks of the observable crust, assumedly of the order of magnitude of 10 or 20 miles thick.

Having thus obtained the norm of the average rock, it is reduced to density by the common method of treatment. The simplest procedure is to multiply the percentage amount of each normative mineral by its density, water being included with a density of 1, if desired, the sum giving directly the approximate density. This was the method adopted by Iddings in his publications referred to below, but it does not lead to strictly accurate results, because we are dealing here, not with weights, but with volumes. The relative densities of the several normative minerals should, therefore, be reduced to specific volumes by taking their respective reciprocals, and each of the respective percentages of the normative minerals multiplied by its specific volume. The resultant average specific volume is changed to density by dividing it into 1—that, is taking its reciprocal.

With the average rocks, of which the chief constituent minerals do not differ greatly in density, the differences between the two methods are not very great in many cases. On the whole, however, the method by specific gravities leads to somewhat higher figures than does that by specific volumes; and this is especially true of the more femic averages, such as those of the ocean floors, in which almost equal amounts of light feldspars and heavy pyroxene, with considerable very heavy magnetite, are present.

This use of the norm for calculating the density of an average rock originated with Iddings, who talked it over some years ago with his colleagues in the quantitative classification. He gives briefly a few of his results, without detailed description of the method, in his work on volcanism, and later published a short account, the last paper to issue from his pen during his life.⁹ He compared the calculated and observed densities of several rocks and found close agreement, except when much biotite or hornblende were present. Eskola¹⁰ finds, however, that there is but an insignificant difference between the calculated normative density and the observed specific gravity in the case of amphibolites, and that the difference may be in either direction.

In the present connection it is of interest to note that, in his "Problem of volcanism" (page 125), Iddings pointed out the application of these calculated densities to the problem of isostasy and noted that "the correspondence between the general character of large series of igneous rocks and the general demands of the theory of isostasy respecting the existence

⁹ J. P. Iddings: *The problem of volcanism*, 1914, pp. 121-125; and *Am. Jour. Sci.*, vol. 49, 1920, p. 363.

¹⁰ P. Eskola: *Bull. Com. Geol. Finlande*, no. 44, 1915, p. 143.

of deep oceans and elevated continents is striking." He expressed the opinion that the correspondence "is in accord with reasonable expectations." Iddings calculated the densities for a few small areas or comagmatic regions: California (2.85), Colorado (2.80), Yellowstone Park (2.85), the Atlantic coast of the United States (2.89), Great Britain (2.91), Fenno-Scandia (2.85), Germany-Austria (2.81), and Italy (2.86), the average compositions of which had been calculated by Clarke,¹¹ and made an estimate of the average density of some oceanic islands, using analyses of rocks from Reunion (3.12) and the Hawaiian (3.12) and Society Islands (3.20). His results are uniformly higher than those arrived at by me, the difference being ascribable to the difference in the method of computation.

In calculating the average densities or specific volumes which are given in the following pages, I have used the normative molecules of wollastonite (CaSiO_3), enstatite (MgSiO_3), and ferrosilite (FeSiO_3), as well as forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4), instead of taking them combined into diopside, hypersthene, and olivine, as in the regular statement of the norm. This was done because the densities of these mixed mineral molecules are additive and vary with the relative amounts of their components; so that more exact and mutually comparable results are obtained by the method adopted here. The normative feldspars present were, of course, calculated from their respective amounts of orthoclase, albite, and anorthite, as in the norm. Especial care was taken to select the most reliable data for the mineral densities, those of pure artificial crystals being adopted when available. Most of the determinations of these were made in the Geophysical Laboratory and are to be found among the various papers which have been published by the Laboratory. Most of the original figures were for specific gravity; these have been corrected to density, as noted below.

In Table I, which follows, are given the densities and specific volumes which were adopted for the present calculations, together with those for other normative minerals, which may be of use in some calculations.

TABLE I.—*Densities and Specific Volumes of normative Minerals*

	δ	v	Remarks
Quartz	2.648	.3776	Natural. Johnston and L. H. Adams, <i>Journal of the American Chemical Society</i> , volume 34, 1912, page 572.
Orthoclase	2.555	.3914	Calculated from analyses of natural adular. H. E. Merwin, private communication.

¹¹ F. W. Clarke: *Proc. Amer. Phil. Soc.*, vol. 51, 1912, p. 217.

TABLE I.—*Densities and Specific Volumes of normative Minerals*—Continued

	δ	v	Remarks
Albite	2.597*	.3851	Artificial. Day and Allen, Carnegie Publication number 31, 1905, page 58.
Anorthite	2.757*	.3627	Artificial. Day and Allen, work cited.
Leucite	2.48	.4032	Natural. Dana, System.
Nephelite	2.619	.3818	Artificial. Bowen, American Journal of Science, volume 43, 1917, page 115.
Corundum	4.00	.250	Natural. Dana, System.
Wollastonite (CaSiO_3)	2.906*	.3441	Artificial. Allen and White, American Journal of Science, volume 21, 1906, page 92.
Enstatite (MgSiO_3)	3.183*	.3142	Artificial. Allen and others, American Journal of Science, volume 22, 1906, page 396.
Ferrosilite (FeSiO_3)	3.90	.2564	Calculated from unpublished analyses of natural enstatite and hypersthene by Adams and Washington.
Forsterite (Mg_2SiO_4)	3.216	.3109	Artificial. Bowen, American Journal of Science, volume 37, 1914, page 498.
Fayalite (Fe_2SiO_4)	4.318	.2316	Natural from Rockport, Massachusetts. Penfield and Forbes, American Journal of Science, volume 1, 1896, page 130.
Magnetite	5.17	.193	Natural. Dana, System.
Ilmenite	4.7	.213	Natural. Dana, System.
Apatite	3.2	.313	Natural. Dana, System.

RESULTS

In Table II are given the average chemical compositions of the continents and of the floors of the Atlantic and Pacific oceans. With them are also given the estimated average altitudes of the continents, as estimated by Wagner,¹² and the average ocean depths, as estimated by Murray.¹³ The average densities, both on a water-free and a water-bearing basis (as explained later), are also given. These values for density and elevation differ somewhat from those given in my former paper,¹⁴ the former because new values have been adopted for the densities of the

* Calculated to density by R. B. Sosman.

¹² H. Wagner: *Lehrbuch der Geographie*, vol. i, 1912, p. 284.

¹³ J. Murray: *Scot. Geog. Mag.*, vol. iv, 1888, pp. 30 and 34.

¹⁴ H. S. Washington: *Jour. Franklin Inst.*, vol. 190, 1920, p. 801.

TABLE II.—*Chemical Averages of Continents and Ocean Floors*

	Earth	North America	South America	Europe	Africa	Asia	Australia	Antarctica	Atlantic islands	Pacific islands
SiO ₂	59.47	60.19	61.36	59.84	58.21	61.92	60.16	53.66	50.59	50.03
Al ₂ O ₃	15.45	15.76	15.20	15.12	15.28	15.49	14.74	16.82	15.81	15.51
Fe ₂ O ₃	3.10	2.88	3.03	3.17	3.52	3.17	2.60	4.01	4.44	3.88
FeO	3.82	3.67	3.30	3.67	3.73	2.75	4.41	5.34	5.79	6.23
MgO	3.51	3.16	3.47	3.61	3.51	2.63	3.76	4.67	5.79	6.62
CaO	5.11	4.81	4.88	4.97	5.09	4.50	5.03	7.59	7.36	7.99
Na ₂ O	3.86	3.90	4.08	3.73	4.83	4.10	3.50	3.58	4.27	4.00
K ₂ O	3.14	3.07	2.69	3.40	3.28	3.23	3.03	2.32	2.31	2.10
H ₂ O+	1.15	1.01	1.04	1.24	1.26	1.23	1.19	0.93	1.47	1.16
TiO ₂	0.91	1.01	0.56	0.83	0.84	0.68	1.01	0.87	1.63	1.96
P ₂ O ₅	0.24	0.26	0.11	0.23	0.20	0.12	0.26	0.17	0.43	0.25
MnO	0.09	0.10	0.12	0.08	0.07	0.10	0.15	0.03	0.04	0.15
M. C.*	0.15	0.18	0.16	0.11	0.18	0.08	0.16	0.01	0.07	0.12
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
δ _a	2.792	2.782	2.783	2.790	2.780	2.769	2.814	2.865	2.888	3.087
δ _w	2.737	2.733	2.732	2.730	2.718	2.705	2.747	2.818	2.810	3.014
Altitude meters	687	700	580	300	650	950	350	?	$\left. \begin{matrix} -4,116 \\ (-1,830) \end{matrix} \right\}$	$\left. \begin{matrix} -4,520 \\ -4,520 \end{matrix} \right\}$
Number of analyses	5,159	1,709	138	1,985	223	114	287	103	56	72

* M. C. indicates the minor constituents. Density (δ_a) refers to a water-free average rock; density (δ_w) to a rock containing water (H₂O+), as in the prior publication.

normative minerals and some corrections have been here taken into account which were not considered before, and the altitudes because Wagner's estimates differ slightly from those of Murray formerly used.

In my former paper the oceanic depths which are represented by the rocks of the Pacific and Atlantic islands were considered to be the average ocean depth. Study of the bathymetrical charts, however, shows that the Atlantic islands from which we have rock analyses rise from either the long central ridge or from what are deeper parts of the continental shelf, while the Pacific islands may be considered to represent more truly the average depth. In the later calculations I have assumed as a basis both the "ridge" depth of the Atlantic (estimated at about 1,000 fathoms) and also its average depth, while the average depth of the Pacific as here given (4,520 meters) is accepted. We shall see later that the more satisfactory results are obtained by using the "ridge" depth of the Atlantic as the basis for calculation.

The averages given in Table II call for some critical comments, so that the reader may the better understand them. Some of them are averages of many analyses, which represent rocks and localities well distributed over the areas and with probably a not undue proportion of analyses of "interesting" rocks. The averages for North America, Europe, and probably Australia would belong among these. Other areas are represented by few analyses and these not well distributed. South America, for instance, has but 138 analyses and these almost wholly from the Andes, British Guiana, and eastern Brazil. Africa is represented by but 223 analyses and almost all of these from localities near the coasts. The same is true of Antarctica, of which we know the rocks only at isolated localities along a narrow coastal fringe, while the petrology, as well as the elevation, of the interior are quite unknown and probably always will be. Asia, by far the largest continent of all, is very meagerly represented, the 114 analyses being of rocks from few and rather "bunched" localities, while the rocks of vast areas, such as the Pamir, Tibet, and much of Siberia, China, and India, are almost unknown. The Atlantic is represented by rocks from but a few islands in the southern part, the basalts of the northern portion not being represented among the data used, although some are now available. While the analyzed rocks of the Pacific are rather well scattered over the area, yet the analyses are very few and many of them are of "interesting" and somewhat unusual rock types, as Iddings pointed out in his last paper.

This matter of the representatives of the various averages, those of the smaller areas as well as those of the larger, is discussed at some length in the professional paper already mentioned. The conclusion arrived at is

that, while a few of the averages are admittedly defective because of the paucity or the selective character of the data, yet the great majority (including all of the averages given above except those for Antarctica and the Atlantic) are probably fairly representative. In any case, as has been said before and as may be repeated, the averages given in these pages are based on the most recent and the largest set of reliable data that are as yet at hand and are the only such averages available, so that they may be accepted provisionally as a proper basis for some discussion and conclusions.

The average density of the earth's crust, so far as it is exposed to our direct observation and as derived from the chemical averages given here, is 2.792, calculated on a water-free basis, while it would be 2.737 if allowance is made for about 1 per cent of "water on ignition" as found in the analyses.

The δ_a value is notably higher and the δ_w value is lower than that given in a former paper,¹⁵ namely, 2.77, in which the water was reckoned. It is thought, however, that the present value (2.792) is the more correct, for several reasons. The selection of values for the mineral densities has been more careful, the water is disregarded, and this δ_a value approaches more closely to that which is obtained for the average when the continental and oceanic averages are weighted for areas. The result of one such calculation, in which the areas of the Pacific and South Atlantic basins (not the islands alone) were taken into account along with the respective areas of the several continents, gave the density as 2.8506 (sp. vol. = .3508). If the areas of the North Atlantic, Indian, and Antarctic oceans were also considered, with proper allowance for their prevailing basaltic rocks, the density would be still higher, probably about 2.95—that is, slightly below the value given here for the Pacific.

It will be seen that the average chemical compositions of the different continents and ocean basins (represented by their islands) differ among themselves, but in different ways and to various extents. The averages for Europe and North America most closely resemble that for the earth; that for South America is much like these, but is slightly higher in silica, while the maximum silica is reached in Asia. The Australian average resembles the preceding in its silica, but is distinctly higher in iron oxides and lower in alkalies, while that for Africa, which is distinctly lower in silica, is decidedly higher in soda. With Antarctica we get a much more femic composition, which is still more marked in the Atlantic and especially the Pacific averages. It is not the place here to discuss these and

¹⁵ H. S. Washington: Jour. Franklin Inst., vol. 190, 1920, p. 807.

similar details, but the various differences show their respective influences in the calculated densities. Thus Africa, with 2 per cent less silica than has North America, shows a lower density because of its greater content in soda and its consequent richness in the specifically light albite molecule, while Australia, with about the same silica as North America, is decidedly denser because of the greater proportion of normative pyroxene.

NORMATIVE DENSITIES AND ALTITUDES

On comparison of the densities with the altitudes, it will be evident that the two, in general, vary inversely, or that the specific volumes and the altitudes vary directly. There are some irregularities, but the general agreement is unquestionable. This may be seen in the figures for the various areas, large and small, whose average chemical compositions and densities have been calculated.

Satisfactory estimation of the average altitudes of most of the various areas has been a matter of great difficulty. Fairly consistent estimates for the continents and ocean depths are given by Murray, Wagner, and others, and Murray also gives estimates for some smaller areas. Gannett gives data for the whole United States and for the several States. The most reliable of all such data were used, reference to them being given in connection with Table III.

For many, if not most, countries there is a dearth of good, or even of any, estimates of the average elevation, and the same is true of particular smaller areas. An attempt was made to remedy this defect by estimating the average altitude of some areas, for which no other estimate was available, from the hypsometric maps in the Times Survey Atlas of the World (London, 1920). These estimates, as well as most of those of the smaller areas, can claim to be nothing more than very rough approximations; they have been used only for lack of more accurate data.¹⁶

In Table III are given the average altitudes in meters and the calculated average densities for 47 areas, including the continents and the floors of the Pacific and South Atlantic. The densities are shown calculated as of rocks both water-free (δ_a) and water-bearing (δ_w); but it may be remembered that the former is that which I prefer and which is most often referred to in later calculations. The number of analyses on which the density calculations are based are also given.

¹⁶ My thanks are extended to Mr. Alan G. Ogilvie for kind assistance in collecting data as to altitudes. I would also thank Dr. A. G. Brooks for his kindness in having the average altitude of Alaska computed at my request.

TABLE III.—*Average Altitudes of Forty-seven Areas*

	<i>h</i> <i>Meters</i>	δ_a	δ_w	Analyses	Altitude references
1. Earth	700	2.792	2.737	5,159	Wagner, 1. Murray gives 2,252 feet = 686.6 meters.
2. North America.....	700	2.782	2.733	1,709	Wagner, 2.
3. Greenland	980	2.783	2.728	41	Murray.
4. Ontario and Quebec..	100	2.869	2.812	99	Canadian Geological Survey maps.
5. Alaska	610	2.750	2.713	24	A. H. Brooks, personal communication.
6. British Columbia....	1,100	2.806	2.749	60	Times Atlas.
7. United States.....	760	2.780	2.730	1,351	Gannett.
8. New England and New York.	230	2.777	2.741	213	Gannett.
9. Appalachia	610	2.778	2.739	188	Gannett, modified.
10. Algonkian region....	250	2.856	2.805	66	Gannett, modified.
11. Arkansas-Texas	230	2.812	2.759	50	Gannett, modified.
12. Montana	910	2.771	2.722	133	Gannett.
13. Wyoming (Yellowstone National Park).	1,820	2.753	2.683	134	Gannett.
14. Colorado	2,134	2.760	2.706	171	Gannett.
15. Utah-Nevada	1,820	2.702	2.639	79	Gannett.
16. Arizona-New Mexico.	1,520	2.760	2.728	79	Gannett.
17. Oregon-Washington..	760	2.809	2.754	51	Gannett.
18. California	910	2.775	2.724	175	Gannett.
19. West Indies.....	250	2.816	2.776	82	Murray.
20. Mexico and Central America.	2,000	2.794	2.742	47	Times Atlas.
21. South America.....	580	2.783	2.732	138	Wagner, 2.
22. Andes	1,820	2.752	2.700	56	Times Atlas.
23. Eastern Brazil.....	750	2.797	2.722	20	Times Atlas.
24. British Guiana.....	125	2.828	2.781	45	Harrison.
25. Europe	300	2.790	2.730	1,985	Wagner, 2.
26. Great Britain and Ireland.	100	2.830	2.758	171	Times Atlas.
27. France	500	2.764	2.706	163	Times Atlas.
28. Scandinavia	600	2.759	2.720	313	Times Atlas.
29. Norway	700	2.763	2.729	107	Times Atlas.
30. Sweden	500	2.758	2.727	206	Times Atlas.
31. Germany	300	2.814	2.744	474	Times Atlas. Compare Ratzel.
32. Austria - Hungary (Tyrol not included).	400	2.817	2.744	148	Kirchoff, modified.
33. Switzerland and Tyrol.	1,550	2.784	2.702	219	Times Atlas.

TABLE III.—Average Altitudes of Forty-seven Areas—Continued

	h Meters	δ_a	δ_w	Analyses	Altitude references
34. Italy (Sicily, Sardinia, etcetera).	500	2.763	2.727	276	Times Atlas.
35. Russia (chiefly Urals).	250	2.968	2.905	98	Times Atlas.
36. Balkania (Greece and archipelago).	800	2.739	2.691	33	Times Atlas.
37. Africa (continental).	650	2.780	2.718	223	Wagner, 2.
38. Madagascar	670	2.828	2.771	140	Murray.
39. Asia (continental)...	950	2.769	2.705	114	Wagner, 2.
40. Japan	430	2.785	2.713	69	Murray.
41. Malaysia and Philip-pines.	650	2.774	2.721	129	Murray.
42. Australia (Tasmania).	350	2.814	2.747	287	Wagner, 2.
43. New Zealand.....	650	2.813	2.729	134	Murray.
44. Antarctica	?	2.865	2.818	103	
45. Atlantic (average depth).	—4,116	2.888	2.810	56	Murray.
46. Atlantic (ridge depth).	—1,830	2.888	2.810	56	Times Atlas.
47. Pacific (average depth).	—4,520	3.087	3.014	72	Murray.

Wagner, 1: H. Wagner. Beitr. Geophysik, volume II, 1895.

Wagner, 2: H. Wagner. Lehrbuch der Geographie, volume I, 1912, page 284.

Murray: J. Murray. Scot. Geogr. Mag., volume IV, 1888, pages 23-38.

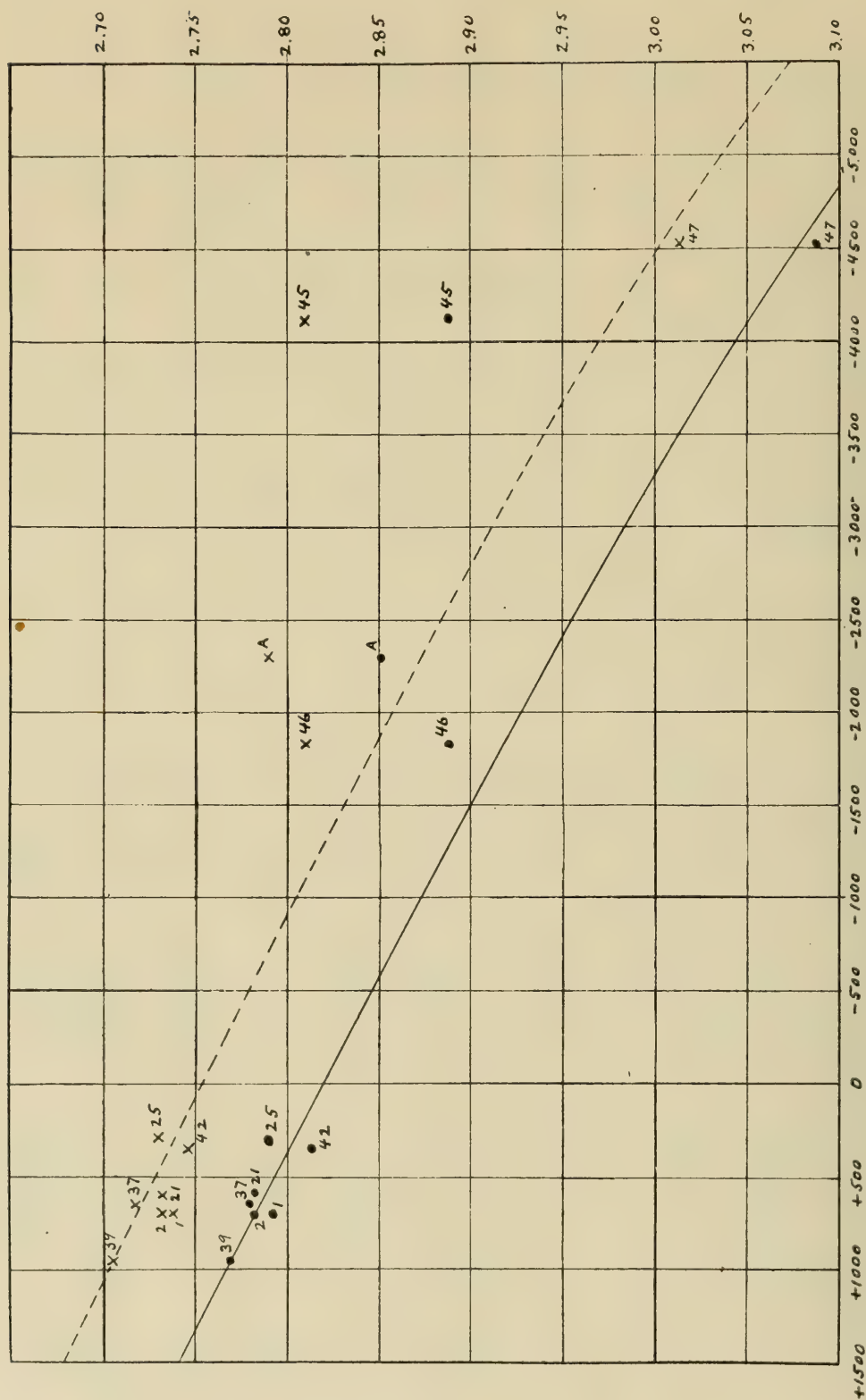
Ratzel ("Deutschland," fourth edition, 1920, page 26) gives 215 meters.

H. Gannett: United States Geological Survey, Annual Report 13, volume II, 1892, page 289.

Harrison: Geological Goldfields of British Guiana, 1908, page 10.

Study of the somewhat numerous data presented in Table III shows that, in general and as applied to various areas all over the earth's surface and of considerable to very large size, the law holds good that *the average density of the igneous rocks of a region varies in the opposite sense as the average altitude*. There are some exceptions, but these are not sufficient to invalidate the broad relation. With no desire to indulge in special pleading, it may be well to consider these exceptions briefly. The representativeness of the individual averages is discussed at length in the unpublished professional paper already mentioned, and the following remarks are mostly abstracts of this.

Some of the apparent exceptions are due to the unrepresentative character of the chemical average. This is true of Utah-Nevada, the density of which is less than Colorado, although its altitude is much lower. The



chemical average of Utah-Nevada, however, is based largely on analyses of decidedly silicic (and therefore light) rocks from mining regions and does not truly represent the very extensive areas of less silicic rocks which form much of the area, while the average for Colorado is one of the most satisfactory that we have. Similarly, the density for Russia is the greatest shown by Europe, much greater than those of areas which are lower or of about the same altitude, as Great Britain, Germany, Algonkian region, Missouri-Texas, and British Guiana. This is doubtless because this large area is represented almost exclusively by analyses of the very "basic" (and therefore heavy) rocks of the Urals, described by Duparc, while there are few analyses of the many granitic rocks of Russia. Balkania (including Greece and the archipelago) seems to be lighter than it should be from its altitude, chiefly because the analytical data include few or none of the numerous gabbros and diorites of the region, but are confined mostly to the lighter and more silicic lavas of the volcanoes. New England (and New York), with a much lower altitude than Appalachia, has about the same density. This correspondence in density may be accounted for by the fact that the New England region is comagmatically a continuation of the Appalachian, as is shown by the similar characters of the granitic and other rocks, while the divergence in altitudes may be ascribed to differences in local tectonic movements. Greenland and Spain appear to be much denser than their altitudes would warrant, but this is unquestionably because the analyses which represent these regions are all of rocks on or near the low-lying coastal borders. In the case of Spain, at least, we know that the high interior plateau is composed largely of granites, of which we have not a single analysis. Antarctica presents the same peculiarity as do the two areas just mentioned. The Algonkian region (about Lake Superior) seems to be slightly heavier than it should be for its altitude, probably because of the few analyses of the somewhat abundant granitic rocks of the region. On the other hand, the Oregonian region should be probably rather denser than is shown here, because there are relatively few analyses of the extensive basalt flows.

The general relations are shown in figures 1 and 2, in both of which the loci for rocks without water are indicated by dots, while those for water-bearing rocks are indicated by crosses, a solid curve corresponding to the former and a dashed curve to the latter. The numbers correspond to those of the areas in Table III.

In figure 1 are presented the data for only the continents and ocean depths, with the hyperbola¹⁷ connecting the calculated loci for the conti-

¹⁷ The line is a hyperbola if we plot (as we do here) with h and δ as variables; it will be a straight line if plotted with d and $h\delta$

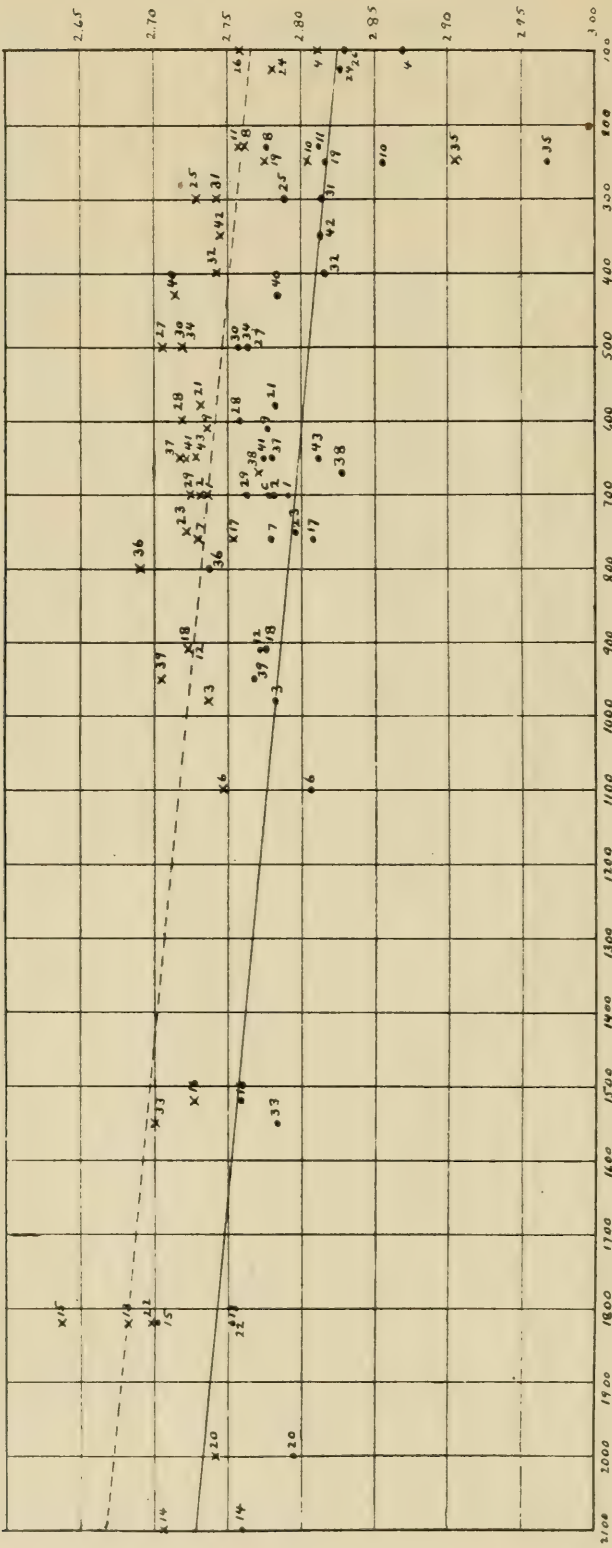


FIGURE 2.—Densities and Altitudes of land Areas

nents and ocean floors, as given in Table V beyond. This line cuts through the little group of continental loci, those for Asia and North America falling on it, and passes a little below the locus for the Atlantic ridge (46) and above that for the Pacific (47). The locus for the earth's crust lies a little below the line, being depressed, as it were, by the density of the material of the ocean floors.

The loci of the Atlantic floor are plotted twice. The locations on the right represent the average depth, while those to the left represent the average depth of the ridges, banks, or continental shelves on which stand the islands from which come the analyzed rocks. The locus of the average Atlantic falls far to the right of the calculated line, while that for the ridges of the Pacific, if plotted, would fall far to the left of it. We are therefore justified in thinking that the altitude which best corresponds to the calculated density of the Pacific floor is that of its average depth, while that for the Atlantic island rocks is the depth of the central ridge, estimated to be about 1,000 fathoms.

The locus (point A in the figure) of the density of the earth's crust weighted for the areas of the continents and for those of the Pacific and South Atlantic oceans (see page 390), and referred for altitude to the average sphere level of the solid earth's crust, —2,300 meters, as calculated by Wagner,¹⁸ falls rather above the line, indicating that the density is too low, because not sufficient weight has been given to the areas of very heavy rocks of all the ocean floors.

In figure 1, as well as in figure 2, the loci and the hyperbolas for the values calculated as rocks with and without water are essentially alike. Those for water-bearing rock fall above those for water-free rock because of the lower densities, and the relative positions of some of the loci are slightly different in the two, but either one would suffice to prove the inverse relation between rock density and altitude.

In figure 2 are shown the loci for 42 land areas, large and small, this figure being an enlargement and extension of the upper left portion of figure 1, the abscissal scale for altitudes being larger. Here, also, we see, in more detail, the general drift, which shows clearly the inverse relationship between the rock density and the average altitude. This is summed up in the hyperbolas,¹⁹ the solid line representing rocks calculated as water-free and the dashed line when calculated as water-bearing. Many

¹⁸ H. Wagner: *Beitr. z. Geophysik*, vol. ii, 1895, p. —.

H. R. Mill (*Scot. Geogr. Mag.*, vol. 6, 1890, p. 185) calculates the "mean sphere level" as 8,400 feet, equal 2,561 meters.

¹⁹ The portions of these included here are so far from the vertices that they are practically straight lines.

of the points, and among these those which are the most satisfactory as to chemical representativeness and average altitude, fall on or near to the hyperbolas, while others lie more or less far from the lines, although roughly along them. We have noted above the probable reasons for the departures in the case of some of the loci, such as those for Utah-Nevada, Balkania, Oregon, Madagascar, the Algonkian region, and Russia. The departures of the others from the calculated positions may naturally be ascribed to errors in the estimated altitudes, to the more or less unrepresentative character of some of the chemical averages (and consequently the average densities), or to both combined.

Notwithstanding all small discrepancies and defects in details, the data given in Table III and the graphic representation in figures 1 and 2 show clearly that *the densities and altitudes vary together in the sense that as the altitudes decreases the density increases, and the converse*, although not with strict proportionality. In other words, our study of the average densities and altitudes shows that the higher parts of the crust are composed of or underlaid by relatively light material, while the lower parts are underlaid by heavier material. This, as was pointed out at the beginning of this paper, is precisely the relation demanded by the theory of isostasy.

An illustration of what appears to be a consequence of this interrelation is to be found in the ancient shields—the nuclei of the continents. It is commonly recognized that these are made up to a large extent of granitic rocks and gneisses, rocks of low density. We have no actual knowledge of the exact chemical composition, and consequently average density, of the rocks of the Canadian shield, but that it is largely composed of the rocks mentioned is too well known to need more than mention. The Baltic shield is composed of the same kinds of rocks. Here, fortunately, we have some detailed knowledge, from numerous descriptions and analyses. The average density of Scandinavia is 2.759—that is, it is one of the lightest land areas whose density we know. Only Utah-Nevada, Balkania, Alaska, and the Andes have lower densities. We know little in detail of the igneous rocks of Angara Land, but here also we know that the prevailing igneous rocks are similar to those of the shields just mentioned, although later extensive basalt flows occur. Much of the same is true of Amazonia, although the eastern present border of this shows a rather high density. Of the rocks of the less well defined Archiplata shield we know little. It is interesting to note, in this connection, that Fisher²⁰ states that the Falkland Islands show a marked negative gravity anomaly, being thus exceptional among island stations. Accord-

²⁰ O. Fisher: The physics of the earth's crust p. 250.

ing to Renard,²¹ the igneous rocks of these islands are largely granitic, and we know that they formed part of the old Archiplata shield.

THE PHYSICAL AVERAGE DENSITY

The so-called physical method of obtaining the average density of a given area is less complex and more direct than the normative method which has been described in the preceding pages. Notwithstanding this, there are such serious objections to it that the description and discussion of it need not detain us long.

According to this method, the available determinations of the specific gravities of the rocks of the area are collected. It matters not whether they have been analyzed or not, nor, if they have been analyzed, whether the analyses are good. Their average is calculated by dividing their sum total by the number of determinations. The specific gravity determinations and the resulting averages may be grouped into separate areas or not, as may be desired for the object in view.

This method is, obviously, of great simplicity, but it would seem that it has never been carried out, at least on a large scale. At first glance, it may appear to lead to more reliable and more consistent results than the normative method. It might be urged, for instance, that in using this method we deal with the actual rocks and with their specific gravities, as directly determined by the balance, whereas by the other method we deal with hypothetical mineral molecules and arrive at our results only by a very indirect route. But the case is not so simple as may be thought, and the physical method is subject to several disturbing factors which may, and usually will, introduce errors of very appreciable magnitude, if we are to use the results in the comparison of the densities of different areas or of rock masses of large size and considerable depth.

One important source of error is the presence of more or less glass in many lavas, some of them being wholly glassy. The glass form of a rock or of a mineral has a density less by a very considerable percentage than the crystalline form. To give an idea of the magnitude of this difference the following figures may be cited from determinations made in the Geophysical Laboratory and published in various papers issuing from it:

Specific Gravities

	Crystalline	Glass
Quartz	2.654	2.213
Albite	2.605	2.382
Anorthite	2.679	2.533
Diopside	3.275	2.830
Diabase	2.975	2.763

²¹ A. Renard: Petrology of oceanic islands, 1889.

Collections of physical determinations of the specific gravities of rocks would include those of many rocks containing glass, so that the average specific gravity thus arrived at would be low. We know that the plutonic rocks, those formed at considerable depths, do not contain glass; and, furthermore, examination of a large series of determinations of specific gravity shows that the specific gravity of effusive lavas is generally less (and by a notable percentage) than the specific gravity of plutonic rocks, such as granite and diorite. Consequently the introduction of specific gravity determinations of such glassy or effusive rocks along with plutonic rocks would introduce serious error for our purpose of comparison of the density of the average rocks of different areas.

For our purpose, it matters not what may lie below, so long as we know nothing of the characters of the deep-lying matter. We can deal only with rocks as we know them, and base our data on ascertained facts and rock characters. As an illustration of the possibility of the introduction of serious error into our data by the use of physically determined specific gravities, let us suppose a case, actual examples of which might readily be found. Consider two areas of the same altitude (and about the same size), the one (A) showing only effusive igneous rocks, say rhyolites, while the other (B) shows nothing but plutonic rocks, let us say granite, the rocks of both being of the same general chemical composition. It is quite obvious on very slight consideration that the average specific gravity (determined physically) of the two will not be the same; that of A will be notably lower than that of B. The two areas, therefore, might appear not to conform to the law demanded by isostasy. On the other hand, if we calculate the densities from average norms, we would eliminate the physical differences caused by the one portion of magma solidifying quickly at the surface and the other slowly at depth; the average normative densities of the two areas of like rocks and of like altitude would be practically identical, which is, *ex hypothesi*, what is to be expected. It must not be lost sight of that the columns with which we are dealing extend far below the surface, so that surface lavas can not properly represent them. It is also true that even the rocks which we call "deep-seated" do not come from very great depths, isostatically speaking; but they are the only data which we have, and it seems the more rational procedure to adopt a method which will reduce all the physically discordant characters to uniformity and to the same conditions as to pressure, rate of cooling, and other controlling factors, rather than to use a method in which this source of error is at a maximum.

Two minor sources of error are the porosity and the weathered condi-

tion of many rocks, disturbing features which would not occur at depth and which are also eliminated by the normative method.

Finally, it is the general rule that a magma crystallizing under plutonic, deep-seated conditions forms mineral aggregates which differ from those which would be formed by the same magma solidifying under effusive, surface conditions. Some examples of this have been given on a preceding page, and the observation is one of the commonplaces of petrography. Its application to the present matter lies in the fact that the two different mineral aggregates—that is, the rocks—would have markedly different densities, so that they would not be mutually comparable for the purposes of investigations in isostasy, in which we must deal with rocks, the majority of which are plutonic.

It follows from this very brief exposition that the results to be obtained by the physical method for densities can not be regarded as capable of forming a very safe base for generalizations as to isostatic compensation. I have, however, computed the average specific gravity²² of 1,849 rocks, of which specific gravity determinations were found along with the analyses in Professional Paper 99 of the United States Geological Survey. The specific gravities of weathered or otherwise altered rocks were not considered, but those of fresh rocks, represented by bad as well as by good analyses, were included, as the quality of the analysis had no bearing on the matter. Many more determinations might have been obtained by search through the literature, but time was lacking for this, and it was thought best to confine the investigation to the same set of data which served for the calculations by the normative method.

It was found that there were far fewer specific gravity determinations than analyses; indeed, the specific gravity determinations used numbered only 1,849, while there were altogether about 8,500 analyses, good and bad, of fresh rocks. It was also found that there were great differences between the various countries as to the numbers of analyses, both absolute and relative to the numbers of analyses. For some countries, notably Germany, Switzerland, Italy, and Australia, specific gravity determinations were fairly numerous, while for others, as the United States, France, Norway, and Sweden, they were very few. It is to be regretted that this feature of igneous rocks, even though it be a minor one, is so frequently neglected. *Peccavi!*

²² In all these cases the specific gravity, not the true density, is given, frequently with no mention of the temperature at which the observation was made; so that reduction to density is impossible. The figures given here are, therefore, specific gravities. The error involved will not be very great, but it is one to be added to the list of errors already set forth.

In Table IV are given the results of the computations for the earth as a whole and for those countries which were represented by the most numerous data. It may be considered that the data for the countries not found in the table are insufficient for proper generalizations.

TABLE IV.—*Average specific Gravities by the physical Method*

	Specific gravity	Altitude	Determinations	δ_a	Normative density δ_w
Earth	2.761	700	1,849	2.792	2.737
United States.....	2.803	760	295	2.780	2.730
British Columbia.....	2.760	1,100	49	2.806	2.749
Andes	2.598	1,820	39	2.752	2.700
Great Britain.....	2.827	100	57	2.830	2.758
Germany	2.790	300	252	2.814	2.744
Austria-Hungary	2.785	400	66	2.817	2.744
Switzerland-Tyrol	2.766	1,550	161	2.784	2.702
Italy	2.680	500	146	2.763	2.727
Balkania	2.614	800	43	2.738	2.691
Malaysia	2.686	650	57	2.774	2.721
Australia	2.775	350	238	2.814	2.747
Atlantic islands.....	2.861	—1,830	34	2.888	2.810

The average specific gravities with water neglected, (δ_a) as determined by the physical method are uniformly lower than the densities determined by the normative method, with the single exception of the United States. For the Andes and Balkania the values are so low that this may be ascribed with confidence to the inclusion of many glassy lavas among the specimens examined, and the same is probably true (but to a less degree) as regards Italy and Malaysia. The normative densities reckoned with water, δ_w , are generally lower than the physical densities.

But, however unsatisfactory these figures may be, the interesting fact appears on confrontation of the specific gravities with the corresponding altitudes, that the general law of inverse relation between density and altitude holds good. The correspondence is not so clear as with the other method, and the law is partly masked by the presence of many glassy rocks, but the general results are in harmony with the conclusions arrived at in the preceding pages.

THE ISOPIESTIC LEVEL

According to the theory of isostasy, the various columns of different densities and heights of which the crust is assumed to be composed balance each other or are of equal weight at a certain depth. This depth is called the “depth of compensation” by Hayford and Bowie. The term “isopiestic level” is suggested here to denote this subcrustal region because

at this level the irregularities in pressure due to local topography flatten out and the pressure of the superincumbent crust is everywhere the same.

The depth of this isopiestic level has been computed by several geodesists by different methods, but always on the assumption that there is equal vertical distribution of density in the column. The results vary within rather wide limits, which is not surprising when the somewhat uncertain character of the data used is considered, but they are all of the same order of magnitude, varying only from about 40 to 122 kilometers. Many years ago O. Fisher²³ estimated the depth at about 25 miles, arriving at this along two lines of reasoning. An early computation by Hayford²⁴ gives 113 kilometers, and a little later he arrives at the value 122 kilometers.²⁵ The latest estimate is that of Bowie,²⁶ who gives the value 60 kilometers (37.28 miles), derived from 216 stations distributed over the United States, as well as the value 96 kilometers (59.65 miles), derived from observations at the stations in mountainous regions of the United States. He accepts the latter (96 kilometers) as the best, for the reason that the values of gravity are more sensitive to change in depth at such elevated stations than at those situated on coastal plains or plateaus.

The depth of the isopiestic level has been calculated from the data arrived at by the normative method and given in Table III. The height of any column of density, δ , is considered to be made up of two portions, the altitude above sealevel, h , and the depth from sealevel to the isopiestic level = M (h and δ being the variables). As the columns are all of equal weight and as M is a constant, we have the general relation: $(M + h) \delta = A$, A being a constant. From this we have:

$$\delta = \frac{A}{M + h}, \text{ and } \delta_0 = \frac{A}{M},$$

δ_0 being the theoretical density of a column whose height is M , or that of an area at sealevel. The process of calculation was the ordinary method of least squares, the equations used being given below.²⁷ It is to be noted that the equation $A = (M + h) \delta$, although linear with respect to $h\delta$ (considered as a single variable) and to δ (the other variable), is, of course, not linear with respect to h and δ as the variables.

²³ O. Fisher: The physics of the earth's crust, second edition, 1889, p. 217.

²⁴ J. F. Hayford: The figure of the earth. U. S. Coast and Geodetic Survey, 1909, p. 175.

²⁵ J. F. Hayford: Supplementary investigation. U. S. Coast and Geodetic Survey, 1910, p. 77.

²⁶ W. Bowie: Investigation of gravity and isostasy. U. S. Coast and Geodetic Survey, Special Publication no. 40, 1917, p. 133; and Amer. Jour. Sci., vol. ii, 1921, p. 5.

²⁷ $A = \frac{\sum \delta^2 \sum h\delta - \sum \delta \sum h\delta^2}{n \sum \delta^2 - (\sum \delta)^2}$; $M = \frac{\sum \delta \sum h\delta - n \sum h\delta^2}{n \sum \delta^2 - (\sum \delta)^2}$,

in which n = the number of observations.

For the suggestion and use of this method and for aid in the calculations, I am deeply indebted to Dr. Leason H. Adams, of the Geophysical Laboratory.

The isopiestic depth was calculated from different sets of data: (1), the continental masses (except Antarctica, for which no reliable estimate of the altitude is possible), with the Atlantic and Pacific Ocean floors; (2), a set of smaller areas,²⁸ selected as among the most reliable for density and altitude, with the ocean floors; and (3), the 11 areas within the United States²⁹ whose densities had been calculated, the ocean floors not being considered in this set. Two different assumptions were made as to the average depth of the Atlantic in dealing with sets (1) and (2). The first was that the depth ($-h_m$) is the mean depth of the whole ocean basin ($-4,116$), and the second was that the depth ($-h_r$) is that of the ridge or shelves on which the islands stand ($-1,830$). The United States area was selected to represent a continental mass, uninfluenced by the density of the ocean floors, because the densities and altitudes of this country are the most reliable among the larger areas. The densities used throughout are those calculated for water-free rock.

Space is lacking to give here in detail all the results of these calculations. We shall consider, as an example, only those for set (1), the continents and ocean floors calculated as water-free. The areas dealt with in this set are the largest, the values for δ and h are probably among the most reliable, there is a fairly wide range in altitudes, and the question of personal judgment and selection of data does not enter.

TABLE V.—*Densities of Continents and Ocean Floors. Water-free Basis*

Area	h Meters	δ_a	δ_m	δ_r	$\delta_a - \delta_m$	$\delta_a - \delta_r$
North America.....	700	2.782	2.767	2.755	+ .015	+ .027
South America.....	580	2.783	2.773	2.760	+ .010	+ .023
Europe	300	2.790	2.786	2.776	+ .004	+ .014
Africa	650	2.780	2.769	2.757	+ .011	+ .023
Asia	950	2.769	2.755	2.746	+ .014	+ .033
Australia	350	2.814	2.784	2.773	— .030	— .041
Atlantic (average).....	—4,116	2.888	3.020	.....	— .132	.....
Atlantic (ridge).....	—1,830	2.888	.....	2.892	.....	— .004
Pacific (average).....	—4,520	3.087	3.044	3.053	— .043	— .054
Sealevel (δ_o)	0	.....	2.801	2.814	.....	.....

Assuming Atlantic average, $M_m = 56.79$ km. = 35.29 miles.

Assuming Atlantic ridge, $M_r = 52.64$ km. = 32.71 miles.

²⁸ Appalachia, Algonkian region, Colorado, Wyoming, Montana, California, Andes, Great Britain, Madagascar, Japan, Malaysia, and New Zealand.

²⁹ New England, Appalachia, Algonkian region, Arkansas-Texas, Montana, Wyoming, Colorado, Utah-Nevada, Arizona-New Mexico, Oregonian region, and California.

In this set of computations and also in (2), of the smaller areas and the ocean floors, the sums of the squares of the residuals for the Atlantic ridge depth are much smaller than that for the average depth of the whole Atlantic. This harmonizes with the results obtained on plotting the data (figure 1), so that we may assume that the depth represented by the analyses of the Atlantic island rocks is more approximately that of the ridge on which they stand (about 1,000 fathoms) than that of the Atlantic as a whole.

The various values for *M* obtained from the several sets of data are presented in Table VI.

TABLE VI.—*Isopiestic Depths*

	Water-free		With water	
	<i>Kilometers</i>	<i>Miles</i>	<i>Kilometers</i>	<i>Miles</i>
1.	56.79	35.29	57.41	35.67
2.	52.64	32.71	52.47	32.60
3.	59.83	37.18	59.25	36.82
4.	55.22	34.31	56.09	34.85
5.	36.20	22.50	33.81	21.01
6.	96	59.65	.....	.....
7.	60	37.28	.....	.....
8.	40.25	25	.....	.....

1. Continents and oceans, average Atlantic depth.
2. Continents and oceans, ridge Atlantic depth.
3. Small areas and ocean floors, average Atlantic depth.
4. Small areas and ocean floors, ridge Atlantic depth.
5. United States area, without ocean floors.
6. Hayford and Bowie, mountain stations in the United States.
7. Bowie, stations distributed over the United States.
8. O. Fisher, estimate by two methods.

The most striking feature of this table is that all the values are of the same order of magnitude; and this general agreement may be accepted as evidence that the values approximate to the truth, especially when it is considered that several very distinct methods have been used in arriving at them. The values obtained by the normative method are in very fair agreement, with the exception of that derived from the United States area; the reason for this we shall see presently. The fairly close agreement between the four normative values for the isopiestic depth in which the ocean floors are considered and the mountain station value of Hayford and Bowie is a point to which attention may be specially directed.

As regards the normative values, it would appear that the values for *M* yielded by the sets of data with large differences in altitude are greater than those yielded by sets in which the differences in altitude are less.

The relation is, however, not so simple, as the influence of varying values of δ comes into play. Inspection shows that the following relations hold good mathematically:

M decreases when $\Delta \delta$ (for constant Δh) increases;

M decreases when Δh (for constant $\Delta \delta$) decreases.

The problem becomes much more complex when both δ and h vary, and when, also, varying numbers of extreme or intermediate data are handled the final result is incapable of exact prediction. We shall see, however, that the actual variation is not great when probable values are assumed for δ and h .

It is a matter of difficulty to decide as to the respective merits of these various values. Those derived from the normative densities can be regarded as but provisional approximations, in view of the tentative and not wholly satisfactory character of some of their basal data. Their general concordance within not very wide limits and their general agreement with the values based on gravity determinations point to their approximate correctness, and also justifies the belief that the normative method is based on sound principles and would be capable of yielding quite satisfactory results were the chemistry and the hypsometry of the igneous areas of the globe better known.

Considering the quality of the data as to density and altitude which are available at present, I regard the values based on a "ridge" Atlantic depth as better than those which are based on the average Atlantic depth. Furthermore, it would seem to be probable that the values arrived at from the set of small areas and the ocean floors are nearer the truth than those arrived at from the continents and the ocean floors, and still more so than those derived from land areas alone. The value derived from the United States alone is so small and so different from the others that it may be neglected. With the small areas, we are dealing with sizes of area which are more commensurate than are the continents with the possible isostatic units imagined by Hayford,³⁰ who speaks of the importance for future study of determining the maximum horizontal extent of areas capable of showing isostatic compensation.

Some considerations may point the way to a decision: First, the material which composes the deep floors of the Atlantic, Indian, and Antarctic oceans is unknown, although we can form some idea of its general character, and it has not yet been taken into account. Second, the density which is here assumed for the Pacific floor is almost certainly too low, because of the undue proportion of "interesting" rocks which were

³⁰ Hayford: The figure of the earth, 1909, p. 169.

analyzed and which are of less density than those which undoubtedly constitute the greater part of the floor—a fact which was pointed out by Iddings in his two papers cited above. Third, we have no data for the average densities of such extremely high columns as those capped by the Tibetan Plateau and the Pamir, which have average altitudes respectively of about 4,500 and 4,000 meters.³¹

Let us now assume reasonable values for these unknown densities, accept the approximately known altitudes (positive or negative) for the new areas, combine them with a set of the densities and altitudes of known areas which will introduce into the equations a fair number and distribution of intermediate data, and calculate a hypothetical value for M , the isopiestic depth, on this basis. I have calculated such a hypothetical isopiestic depth, using the following *assumed* data: Tibetan Plateau, $h = 4,500$, $\delta = 2.60$; Pamir, $h = 4,000$, $\delta = 2.65$; Atlantic, average depth, $h = -4,100$, $\delta = 3.00$; Pacific, extreme depth, $h = -5,500$, $\delta = 3.25$. With these were reckoned the values of h and δ for Colorado, Wyoming, Montana, Appalachia, Japan, Great Britain, the Atlantic ridge, and the average Pacific, as given in Table III. We are thus using quite possible—indeed, quite probable—extremes and have a fair number of reliable intermediate data fairly well scattered as to altitude. Calculation by the method used in the other cases yields the values: $M = 58.99$ kilometers and $\delta_0 = 2.830$. The densities for water-free rock were used, but, as we have seen above, the difference between this result and that from using water-bearing rock is so small as to be negligible for our purpose.

It is not probable that the extreme values here assigned for h and for d will ever be greatly changed. The altitudes can not be far wrong, and we have assigned to the Tibetan and Pamir heights rock densities which are about as low as can be considered possible for holocrystalline rocks. The value for the material of the floors of the Pacific and other oceanic “deeps” may be changed when or if we obtain some direct knowledge in the future as to the exact characters of the rocks that compose them; but it is not probable that the value here assigned, which exceeds that of most basaltic rocks, can be greatly increased.

The close correspondence between the value so obtained, 59 kilometers, and that of Bowie, 60 kilometers, from gravity determinations at 216 stations distributed over the United States, is obvious. The correspondence may be fortuitous, but it may be permitted to express the belief that it has a firmer basis than mere chance, and that it expresses the approxi-

³¹ A. Heilprin: Lippincott's Gazetteer, 1906, pp. 1397 and 1832.

mate truth. We seem, then, to be justified in assuming that the best normative value for the isopiestic depth is 59 kilometers, and we may accept 60 kilometers, about 37 miles, the value of Bowie, as the nearest approximation to the true isopiestic depth.

It need not be attempted to explain the difference between the value of 60 kilometers, arrived at by the normative method and gravity methods from many stations, and that of 96 kilometers, accepted as the best by Bowie. The probability of such a high value as 96 kilometers being the more correct may, however, be roughly tested. We have noted above that M decreases when $\Delta \delta$ increases, Δh remaining constant; so that M will increase as $\Delta \delta$ decreases. We may then substitute in the hypothetical data just dealt with, and which yielded the value $M = 58.99$, such values for d at the extreme altitudes which will give the minimum difference between them, the densities being at the same time petrologically possible and the general truth of the law of isostasy being assumed. This has been done, increasing the values for Tibet to ($\delta = 2.70$) and Pamir to ($\delta = 2.75$) and decreasing that for the deep Pacific to ($\delta = 3.10$). It is thought that no higher or lower values can be reasonably accepted for these respective extreme areas. Calculation from these data (the intermediate ones being the same as before) yields the value $M = 77.07$, which is about half way between Bowie's accepted value and mine. That is to say, we have given great advantage to Bowie's value and we get only half way to the higher figure. One might assume still higher and lower values for the densities of the rocks of the extreme heights and depths, and might finally obtain a value of about 96 kilometers; but it seems to be unnecessary to do this, as it would be of no significance.

It is, however, significant that the depth of compensation as estimated by Hayford and by Bowie at different dates tends to "decrease successively as the amount of data has increased with the lapse of time, and as successively more powerful analyses of the data have been made."³² This is shown below in tabular form.

Date	Depth, kilometers	Reference
1906	141.5	Hayford, Proceedings of the Washington Academy of Sciences, volume 8, page 31.
1909 (April)	113.0	Hayford, Figure of the Earth, page 146.
1909 (December)	122.2	Hayford, Supplementary Investigation, page 54.
1912	113.7	Hayford and Bowie, Special Publication Number 10, pages 10 and 103.
1921	$\left\{ \begin{array}{l} 96 \\ 60 \end{array} \right\}$	Bowie, Special Publication Number 40, page 5.

³² I am indebted to Dr. Hayford for the suggestion of laying emphasis on this trend of the successive estimates.

This generally successive decrease in estimated depth with increased number of available data suggests very evidently "the trend of the successively accumulating evidence," and indicates that the estimates are approaching a limiting value. We are thus justified in believing that the value of 60 kilometers is a fairly close approximation to the truth. This value, it is of some interest to note, also approaches more nearly than those of Hayford and Bowie to Fisher's early estimate of 25 miles = 40 kilometers.

All the estimates of the depth of the isopiestic level which have been discussed in the preceding pages are based on the assumption that the density remains constant throughout the length of the column. If, however, there be some sort of "gravitative adjustment," whereby the density increases with depth, the estimates of the depth of the isopiestic level must be modified; and the modification would depend on the mode and rate of change in density with increase in depth, whether percentually gradual, or by successive discrete steps. Assuming a gradual percentual increase, which seems to be the most plausible for depths of the order of magnitude down to that of the isopiestic level, the centers of gravity of the columns would be lowered, those of the longer and lighter columns more than those of the shorter and heavier ones, so that there would be a virtual lessening of Δh . In accordance with the generalization noted on page 406, by which M decreases when Δh (for constant $\Delta \delta$) decreases, it is to be expected that M also would decrease, thus bringing the isopiestic level nearer the surface.

It is quite impossible to form any estimate, even of the roughest sort, as to the possible extent of such a diminution in isopiestic depth brought about by gravitative distribution of densities. We know nothing of the rates of change in density with depth or of the downward limit which such a change might approach. Indeed, we are still uncertain whether such gravitative adjustment exists, as advocated by Daly, Bowen, and others, although there is much to be said in its favor. It is a factor in the problem which must be taken into account (when possible), but which has been overlooked by geodesists.

COMAGMATIC REGIONS AND GRAVITY ANOMALIES

A few words may be devoted to a somewhat striking illustration of the correspondence between the distribution of igneous rocks into comagmatic regions and the excess or deficiency of gravity, called gravity anomalies.³³ Gravity anomalies, or departures from the theoretical value of gravity

³³ H. S. Washington : Jour. Franklin Inst., vol. 190, 1920, p. 813.

after correcting for latitude, altitude, topography, and isostatic compensation, are called positive when there is an apparent excess of mass or density, and negative when there is a deficiency of mass or density.

This is shown by plotting the co-anomalic lines, as has been done by Bowie for the United States, and republished by Barrell.³⁴ When such an isanomalic map is compared with the distribution of comagmatic regions in the United States, some very striking correspondences appear.

A long, narrow belt of negative anomaly runs parallel to the Atlantic coast along the Appalachian region and is continued (with a break in New York, eastern Pennsylvania, and northern New Jersey) into New England. As we have seen, the rocks of the Appalachian region are relatively light. To the east of this zone are patches of positive anomaly, which may be supposed to be connected with the magma furnishing the extensive Triassic traps of this area. West of it is another positive patch, which corresponds with the sporadic occurrences of peridotites and other heavy rocks in the region east of the Mississippi, as in Kentucky, Pennsylvania, and central New York. A small positive patch covers the Adirondacks, which form an outlier of the rather heavy region of Ontario-Quebec.

Around Lake Superior there is an area of very high positive anomaly, which corresponds very closely with the very heavy, iron-rich rocks of the Algonkian region. South of this a small elongated area of high negative anomaly coincides well with the Ozark uplift, the igneous rocks of which are of low density. Farther west the gravity relations become somewhat more complex, as do the comagmatic relations, but there is a general correspondence, shown in the broad area of negative anomaly which covers the plateau region of Utah, Nevada, Arizona, New Mexico, and part of Colorado, the rocks of which are of very low density. The small patch of very high positive anomaly south of Puget Sound may well be connected with the extensive basalt flows of the Oregonian region.

Further detailed discussion of these correspondences must be left to the future, but sufficient agreement has been shown to indicate that there apparently exists in the United States a close correlation between comagmatic regions (and hence their areal densities) and gravity anomalies.

In closing this paper it is a pleasure to express my sincere appreciation of the invaluable assistance of my colleague, Dr. Leason H. Adams. We have discussed much of the matter together, and the paper owes a good part of what value it may possess to his thoughtful suggestions.

³⁴ J. Barrell: *Jour. Geol.*, vol. 22, 1914, p. 153.

THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS, 1922

President:

CHARLES SCHUCHERT, New Haven, Conn.

Vice-Presidents:

HENRY S. WASHINGTON, Washington, D. C.

ROBERT T. HILL, Glendale, Calif.

W. D. MATTHEW, New York City

T. L. WALKER, Toronto, Canada

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History,
New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1922)

T. W. VAUGHAN, Washington, D. C.

GEORGE F. KAY, Iowa City, Iowa

(Term expires 1923)

L. C. GRATON, Cambridge, Mass.

G. D. LOUDERBACK, Berkeley, Calif.

(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio

BULLETIN

OF THE

Geological Society of America

VOLUME 33 NUMBER 3
SEPTEMBER, 1922



JOSEPH STANLEY-BROWN, EDITOR

PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

NOV 22 1922

CONTENTS

Pages

Old and New Standards of Pleistocene Division in Relation to the Prehistory of Man in Europe. By Henry Fairfield Osborn and Chester A. Reeds - - - - -	411-490
Stages of the Ice Age. By Warren Upham - - - - -	491-514
Late Pleistocene History of the Lower Mohawk and Middle Hudson Region. By James H. Stoller - - - - -	515-526
Kennecott Glacier of Alaska. By Alan M. Bateman - - -	527-540
Map of the Pleistocene Lakes of the Basin-and-Range Province and Its Significance. By Oscar E. Meinzer - - -	541-552
Reconnaissance of the Eastern Andes Between Cochabamba and Santa Cruz, Bolivia. By Kenneth C. Heald and Kirtley F. Mather - - - - -	553-570
Trenton of Central Tennessee and Kentucky. By Percy E. Raymond - - - - -	571-586
Peneplains and the Geographical Cycle. By W. M. Davis -	587-598
Variations or Specific Distinctions: Which? By Richard Swann Lull - - - - -	599-604
Volcanic Ash Bed in the Ordovician of Tennessee, Kentucky, and Alabama. By Wilbur A. Nelson - - -	605-616
Graphic Study of Igneous Rock Series. By Frank F. Grout	617-638
Correlation of the Jurassic Formations of Western Cuba. By Barnum Brown and Marjorie O'Connell - - - - -	639-664

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

Subscription, \$10 per year; with discount of 10 per cent to institutions and libraries and to individuals residing elsewhere than in North America. Postage to foreign countries in the postal union, forty (40) cents extra.

Communications should be addressed to The Geological Society of America, 77th Street and Central Park, West, New York City, or care of Florida Avenue and Eckington Place, Washington, D. C.

NOTICE.—In accordance with the rules established by Council, claims for non-receipt of the preceding part of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C., under the Act of Congress of July 16, 1894.

Acceptance for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

OLD AND NEW STANDARDS OF PLEISTOCENE DIVISION IN RELATION TO THE PREHISTORY OF MAN IN EUROPE ¹

BY HENRY FAIRFIELD OSBORN AND CHESTER A. REEDS

(*Presented before the Society December 30, 1921* ²)

CONTENTS

	Page
I. Old and new standards of Pleistocene division.....	413
Introduction.....	413
1. Glacial correlations of Geikie, Penck and Brückner, and Depéret.....	414
2. Peri-Alpine time standards of Penck and Brückner as inter- preted by Depéret.....	415
Adoption of theory of four glacial advances..	415
Terraces.....	417
Postglacial Period.....	417
Fourth Glacial Period (IV).....	418
Third Glacial Period (III).....	418
Second Glacial Period (II).....	418
First or most ancient Glacial Period (I).....	419
Conclusion.....	419
3. Leverett's comparison of North American and European glacial deposits.....	419
4. Correlation of British and North European Quaternary de- posits of Brooks.....	421
5. New chronologic divisions proposed by Depéret.....	422
Review and summary of Depéret's proposed chronologic subdivision of the Quaternary.....	422
Marine Quaternary of the French and English Atlantic coasts.....	425
Land connections across the British Channel.....	426
Coordination.....	426
Relation of terraces to moraines.....	429
Synchronism of Alpine and Scandinavian advances....	430

¹ Manuscript received by the Secretary of the Society May 5, 1922.

² This paper was presented before the Society in abstract by the junior author, Dr. C. A. Reeds.

The manuscript and illustrations were completed April 15, 1922. The manuscript was revised by Frank Leverett (geology) and N. C. Nelson (archeology). Critical notes by American geologists were added as an appendix, to April 15, 1922.

	Page
Depéret's correlation of northern moraines and Mediterranean Quaternary shorelines.....	431
Depéret's interpretation and correlation of the British Quaternary.....	434
Summary of Depéret's conclusions, geology and archeology	438
6. Postglacial geochronology of Sweden, Finland, and North America of G. De Geer.....	439
II. Correlation of the time divisions with human industries.....	443
1. Correlation of the Penck and Brückner time divisions with human industries.....	443
2. Correlation of the Depéret and Mayet time divisions with human industries.....	450
Correlation: Chellean industry = Second Interglacial Period = Terraces of 28-32 meters.....	450
Correlation: Acheulean industry = Middle and upper portions of terraces of 28-32 meters beginning with close of Glaciation III (Riss) and ending with approach of Glaciation IV (Würm).....	455
Acheulean arrival in Belgium.....	457
Correlation: Mousterian industry = Beginning at the end of arid lower loess and extending through IV Glacial Maximum (Würm of Penck, Monastirian of Depéret) = Terraces of 18-20 meters.....	461
Correlation: Aurignacian industry = Recession of Glaciation IV (Würm) continued into beginning of Postglacial time = End of Monastirian stage of Depéret = Terraces 18-20 meters.....	463
Correlation: Solutrean industry contemporaneous with late Aurignacian and early Magdalenian industries = Second arid or "Middle Loess" Period = Achenschwankung and Bühl of Penck.....	466
3. Correlation of the De Geer geochronology with human industries.....	467
4. Theoretic correlation of Quaternary geology, archeology, and mammalian paleontology, according to our knowledge of 1921, by Osborn and Reeds.....	470
III. Appendix: Review and critique of the Penck-Brückner, De Geer, Depéret systems, from notes by Leverett, Alden, de Martonne, Johnson, and Davis.....	472
Commentators on the paper.....	472
Views of Frank Leverett, of the U. S. Geological Survey.....	472
Views of William C. Alden, of the U. S. Geological Survey.....	479
Views of Emmanuel de Martonne and Douglas W. Johnson.....	479
Discussion by Frank Leverett.....	482
Discussion of the Eustatic theory by W. M. Davis.....	483
IV. Bibliography.....	486

I. OLD AND NEW STANDARDS OF PLEISTOCENE DIVISION

INTRODUCTION

A matter of supreme human interest in anthropology at the present time is the appearance of man in the successive stages of the geologic history of Eurasia and of Africa. The chief object of the present paper is to submit a summary and synthesis of the most recent interpretations in the European Quaternary, both in their bearing on the prehistory of man and as *time standards* of importance to students of American Pleistocene geology and physiography. The recent coordinations of Depéret have set a new basis of time division for the whole Quaternary. The researches of De Geer establish the past fifteen millennia. When combined they support, with certain modifications, the pioneer work of Penck and Brückner. This paper opens with a review of the progress of opinion from 1901 to 1921; it presents a precise statement of Depéret's contributions of 1918 to 1921 and of De Geer's contributions of 1910 to 1921. The manuscript is entirely the work of the senior author. The maps and synthetic diagrams are entirely the work of the junior author.³

In 1915 the senior author⁴ published his "Review of the Pleistocene" (Osborn, 1915.1), and in November of the same year his "Men of the Old Stone Age" (Osborn, 1915.2), in which the existing knowledge of Pleistocene chronology was reviewed and more or less precisely summarized. At the same time the junior author prepared a number of maps and diagrams graphically presenting the chronology of Penck and Brückner. Since 1915 great progress has been made in anthropology; also an original and important contribution to the theoretic division of the Quaternary has been made by the distinguished French geologist and paleontologist, Charles Depéret, of the University of Lyons (Depéret, 1918.1-5, 1919.1, 1920.1, .2, 1921.1), to whom we were previously indebted (1908.1-3, 1909.1) for the most satisfactory subdivision of the Tertiary of western Europe, analyzed and extended by Osborn (Osborn, 1910.1).

The historic bases of Pleistocene subdivision have been the following:

- (1) Astronomic: as in the studies of Croll (Croll, 1875.1), Wallace (1880), and others.

³ Both the preliminary and the final manuscript have been submitted to Mr. Frank Leverett and valuable annotations and corrections have been made at his suggestion. He is not disposed to favor the substitution of the Depéret standard for that of the Penck-Brückner, not at least until it has been given careful field confirmation.

⁴ This is the sixteenth contribution of the same author to the geologic and faunal relations of Europe and America, the previous papers being listed in the *Bibliography* of Henry Fairfield Osborn, 1877-1915, p. 25 (1916.1).

- (2) Paleogeographic: epirogenic movements—that is, continental elevation (marine regression) and subsidence (marine transgression).
- (3) Sealevel changes: eustatic movements—that is, negative (marine regression); positive (marine transgression), Suess (1885.1), Schuchert (1910.1), de Lamothe (1899.1, 1901.1, 1911.1, 1916.1, 1918.1), Gignoux (1913.1), Daly (1920.1,2), Depéret (1918-1921).
- (4) Paleometeorologic: atmospheric (for example, Chamberlin, 1907) and climatic change, due to 1 and 2.
- (5) Glacial and interglacial phenomena, Geikie (1894.1, 1914.1), Penck and Brückner (1909.1), Leverett (1910.1), and others, correlated with 1 to 6.
- (6) River terraces: erosions and deposits, correlated with 1 to 3.
- (7) Other continental geologic deposits: fluviatile sands, moraines, clay laminae (for example, De Geer, 1910-1921), loess, correlated with 1 to 5.
- (8) Paleobotanic: terrestrial and aquatic flora, correlated with 1 to 6.
- (9) Paleontologic: *invertebrate* fauna in marine shorelines (Depéret), fluviatile and continental deposits, correlated with 1 to 7.
- (10) Paleontologic: *vertebrate* fauna and migrations, terrestrial and fluviatile, correlated with 1 to 8.
- (11) Archeologic: succession of human industries in stone and bone, correlated with 1 to 9.
- (12) Anthropologic: evolution and migration of human races, correlated with 1 to 10.

As Quaternary time was passing these *twelve* or more bases of subdivision were constantly interrelated; consequently each makes its contribution to chronology. It becomes evident that the time is not far distant when we shall enjoy a complete correlation not only of contemporary events in western Europe, but of those of North America as well. This correlation will spring from a synthesis of all phenomena and will be entirely consistent with all the facts derived from each series of phenomena. Meanwhile we require as a working basis *one primary standard of division*. Between 1901 and 1918 that of Penck and Brückner prevailed. The object of the present review is to set forth the *new* primary standard proposed by Depéret (1918-1921) and to show its points of agreement and difference with that of Penck.

1. GLACIAL CORRELATIONS OF GEIKIE, PENCK AND BRÜCKNER, AND DEPÉRET

We may open with a tabular summary of the conclusions of James Geikie (1894.1, 1914.1) compared with those of Penck and Brückner (1909.1) and the most recent conclusions of Depéret (1918.1-5, 1919.1, 1920.1,2, 1921.1).

The significance of this summary will be made clear in the concluding analysis of Depéret's work on page 470 of the present paper.

Scandinavian

J. Geikie, 1894-1914

IV GLACIATION = Mecklenburgian

Relatively restrained, local glaciers in the British Isles, in the diverging valleys of the Highlands and the Grampians; large terminal moraines in Denmark, Schleswig-Holstein, northern provinces of Germany, and Russia. Glaciers of Scotland and Norway not joined. [Several moraines of north Germany that are included by German geologists in the last glaciation are outside the limits of Geikie's Mecklenburgian.—LEVERETT.]

III GLACIATION = Polonian

Less extensive than GLACIATION II; northern Britain beyond the midlands shrouded in ice. [These British moraines appear to be the correlatives of the outer moraines of the last glaciation in north Germany. They appear to be younger than the "Middle Drift" of north Germany and also younger than the Riss drift of the Alps. The "Middle Drift" and Riss drift appear to be correlatives.—LEVERETT.]

II GLACIATION = Saxonian

The most extensive; in England united glaciers of Scandinavia and Scottish Highlands extending southward to the Thames, depositing there the "Old Drift" or "lower Boulder-clay"; in Germany extending to the foot of the Harz Mountains, Bohemia, and Saxony, spreading eastward over the Russian plain to Moscow, and joining the Ural glaciers. "Old," or Saxonian, drift, the most external ground moraine.

I GLACIATION = Scanian

The least extensive; along the basin of the Baltic Sea, spreading only to Scania and the German plain through Hamburg and Berlin; not reaching the British Isles. [Wahnschaffe (1909.1) and Leverett (1910.1) find the equivalent of the Günzian in well borings near Berlin and near Hamburg, Germany. Gagel (1913.1) finds no equivalent of the Günzian on the German plain.]

TABLE I

CORRELATION OF THE SCANDINAVIAN AND ALPINE GLACIAL MORAINES

Scandinavian

J. Geikie, 1894-1914

Alpine

Penck, 1901-1909

Depéret, 1918-1921

IV GLACIATION = Mecklenburgian

Relatively restrained, local glaciers in the British Isles, in the diverging valleys of the Highlands and the Grampians; large terminal moraines in Denmark, Schleswig-Holstein, northern provinces of Germany, and Russia. Glaciers of Scotland and Norway not joined. [Several moraines of north Germany that are included by German geologists in the last glaciation are outside the limits of Geikie's Mecklenburgian.—LEVERETT.]

= Würm

Moraines strong ridges, strewn with boulders of all classes; weathered to 0.5 meter in certain areas. Low river terraces (*Niederterrasse*) are conspicuous features throughout entire circuit of Alps. Seldom ravined. Within the Alps moraines mark stadia: Bühl, Gschnitz, and Daun.

= Würmian

Internal moraines in constant relation with low 18-20-meter terraces (*Niederterrasse* of Penck) destitute of loess; terraces generally between 15 and 20 meters above valleys of great water-courses. The internal glaciation is surely the Würm, as maintained by the 15-20-meter altitudes of the terraces to which it is related.

III GLACIATION = Polonian

Less extensive than GLACIATION II; northern Britain beyond the midlands shrouded in ice. [These British moraines appear to be the correlatives of the outer moraines of the last glaciation in north Germany. They appear to be younger than the "Middle Drift" of north Germany and also younger than the Riss drift of the Alps. The "Middle Drift" and Riss drift appear to be correlatives.—LEVERETT.]

= Riss

Features of Riss drift are variable. High terraces (*Hochterrasse*) about 30 meters, but in places 55 to 60 meters, above river beds, represent glacial outwash from the Riss moraine; weathered to 1 to 2 meters, with passage to unweathered portion abrupt. Limestone pebbles absent in weathered portion of Riss, not so of Würm. In many places loess rests on weathered Riss drift.

= Rissian

Frontal moraines in constant relation with terraces (*Hochterrasse* of Penck), which dominate by an average of 20 meters the Würm moraines, attaining in consequence a relative altitude of 30 to 35 meters. The intermediate glaciation (*Neorissian*, Depéret) corresponds to the 30-meter terraces—that is, the true Rissian of Penck.

II GLACIATION = Saxonian

The most extensive; in England united glaciers of Scandinavia and Scottish Highlands extending southward to the Thames, depositing there the "Old Drift" or "lower Boulder-clay"; in Germany extending to the foot of the Harz Mountains, Bohemia, and Saxony, spreading eastward over the Russian plain to Moscow, and joining the Ural glaciers. "Old," or Saxonian, drift, the most external ground moraine.

= Mindel

Most extensive generally of the four glacial stages on the Alpine foreland, but was surpassed by the Riss glaciation in the Lyons region and western Alps; connects with extensive outwash deposits, the younger *Deckenschotter*; preserved in narrow valley strips about 50 meters above the present stream; no limestone pebbles remaining in weathered upper 4-meter zone; granite and gneiss pebbles are present but rotten.

= Mindelian

Terminal moraines east of the Alps in constant relation with terraces (*jungerer Deckenschotter* of Penck), 20 to 25 meters above the Rissian terraces—that is, with a relative altitude of 50 to 60 meters. Hence the external moraines of the Lyons region, in relation to the terraces of 55 to 60 meters, belong to the Mindelian glaciation and not to the Rissian, as supposed by Penck and Brückner. [Leverett still is of the same opinion as Penck and Brückner, because of fine state of preservation of the moraines and terraces in the Lyons region.]

I GLACIATION = Scanian

The least extensive; along the basin of the Baltic Sea, spreading only to Scania and the German plain through Hamburg and Berlin; not reaching the British Isles. [Wahnschaffe (1909.1) and Leverett (1910.1) find the equivalent of the Günzian in well borings near Berlin and near Hamburg, Germany. Gagel (1913.1) finds no equivalent of the Günzian on the German plain.]

= Günz

Günz drift almost completely covered by later drift, but its glacial outwash, the older *Deckenschotter*, is preserved in the highest terraces; also along divides between streams, in narrow strips and small isolated areas; altitude, nearly 100 meters above present stream; average thickness, 30 meters, representing a prolonged and vigorous glaciation. Weathering and solution have removed granite and other pebbles to a depth of a few meters.

= Günzian

Moraines frequently giving rise to terraces (*alterer Deckenschotter* of Penck), whose altitude generally attains 90 to 100 meters above the existing river levels. It appears probable to Depéret that the deposits of the still older alluvium have been in some places confused by Penck and Brückner with this older *Deckenschotter*.

2. PERI-ALPINE TIME STANDARDS OF PENCK AND BRÜCKNER, AS
INTERPRETED BY DEPÉRET*Adoption of Theory of four glacial Advances*

We may now give an abstract from the observations of Depéret (1918-1921) in their points of agreement and disagreement with the classic observations of Penck and Brückner (1901-1909). We give a fuller exposition of Depéret's work, beginning on page 422 of the present paper. The square brackets [] indicate interpolations or comments by the present authors.

First, it is interesting to observe that Depéret and Mayet adopt the theory of four glacial advances, maintained by Penck and Brückner, in Europe. We refer to two recent papers by one of Depéret's former students and present colleagues, Dr. Lucien Mayet, of Lyons (1921.1, 1921.2), from which we may make extensive citations, since he has set forth the Penck and the Depéret standards with the clearness, precision, and brevity characteristic of French scientific writers in general.

As Mayet observes (1921.2, page 482), it is not necessary to review the work of glaciologists of the last half century—for example, the publications of Falsan and Chantre, who limited the Alpine glaciers to a single great extension, in contrast to the pioneer, Geikie, who maintained six glacial periods and five interglacial phases. One of the distinguished French paleontologists, Marcellin Boule (1921.1), recognizes only three main glacial periods, the first of which is placed in Pliocene time (see Table VIII).

The researches of Du Pasquier, of Penck and Brückner, of Depéret, and of Kilian on the peri-Alpine region (see figure 1) relate to the fluvio-glacial complexes, their morainal formations (*vallum, amphithéâtres*, etcetera⁵), their layers of transitional alluvium (*cônes de transition et terrasses constituant celles-ci*). In the valleys of this same peri-Alpine zone one observes a self-staged series of terraces. The *highest* above the present stream-bed belong to the *external moraines* (those most remote from the central Alpine *massif*), which mark the maximum of glacial extension and are the most ancient; also the *lowest* terraces, which approach most closely the actual level of the existing rivers and are related to the *internal moraines* (that is, moraines within the preceding, nearer the central Alpine *massif*), which testify to a less extension of the glaciers and are more recent in age. Similar observations may be made, with perhaps even more precision, in certain valleys of the Pyrenees.

⁵ Vallon = dale; amphithéâtres = cirques.

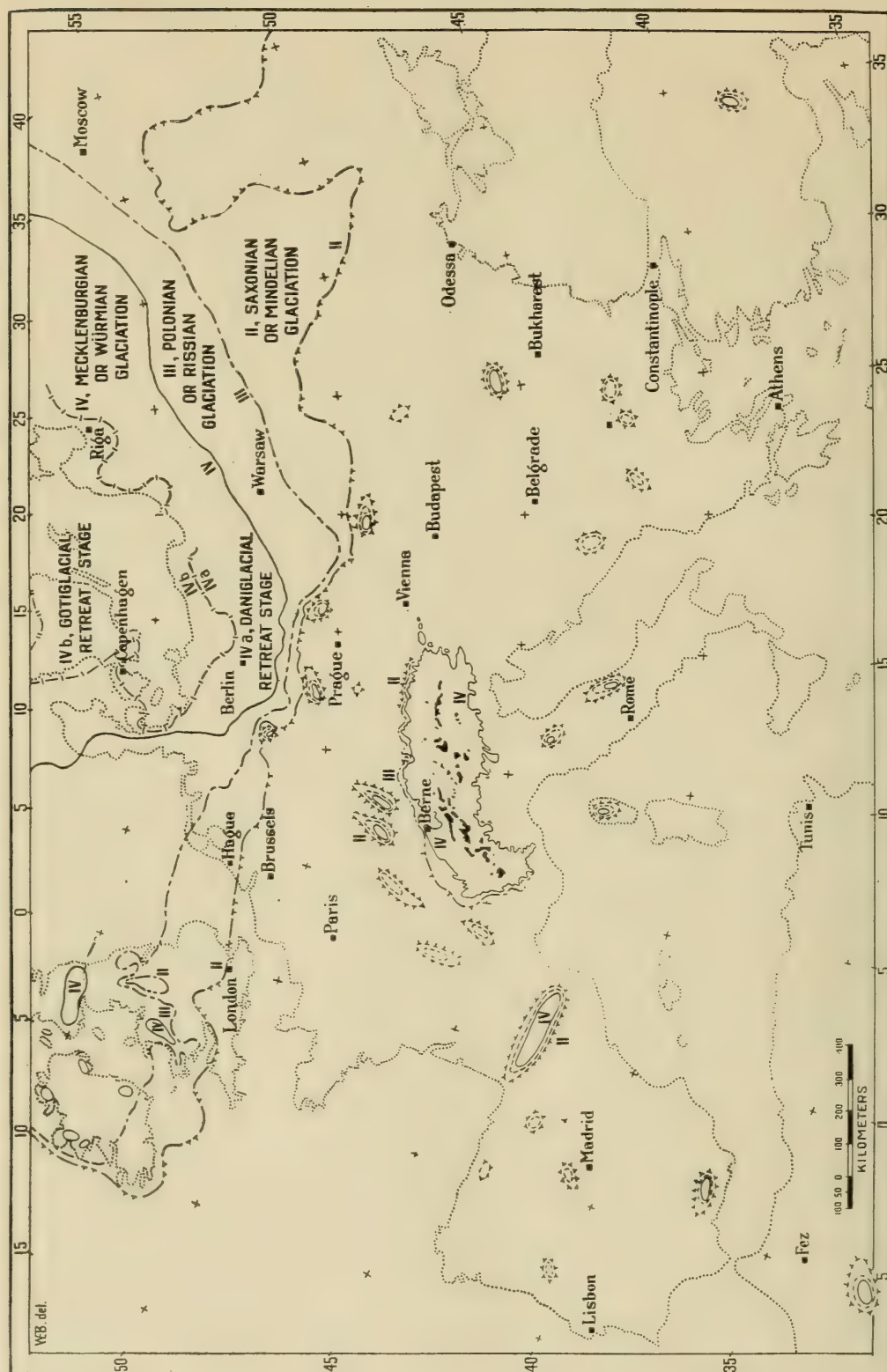


FIGURE 1.—*Map of Central and Southern European Glaciations*

There are shown thereon the II, III, and IV major advances of northern Europe, the Alps, the Pyrenees, and outlying areas; IVa, the Daniglacial; IVb, the Gottiglacial retreat stages of the IV; in solid black, the present Alpine glaciers (after De Geer, 1921).

One may observe, moreover, four sheets or deposits of gravel (*nappes de cailloutis*) standing at four different levels and related to four distinct morainal formations, which are sometimes separated by considerable spaces—that is, by notable differences of altitude. These four deposits of gravel (*nappes de cailloutis*) correspond to four different glaciations (*alluvionnement glaciaire*). During the *first phase* of each interglacial recession period there is produced an erosion (*creusement*), more or less intense, but always rapid, by the abundant water-floods born in the fountain of ice and establishing their stream-bed in the glacial pebbles (*cailloutis glaciaire*).

Terraces

On either side of the glacial stream, against the declivity of the valley, there may persist a part of the glacial layer not encroached upon and not transported by the stream. Thus is constituted the *terrace*, a witness to the topographic surface built up in course of the *preceding glaciation* and connected with the moraines of the same glaciation. For example, as we ascend the river, the terraces are related:

- (a) to the *outer moraines* of GLACIATION II, the terraces at levels of 50–60 meters;
- (b) to the *intermediate moraines* of GLACIATION III, the terraces at levels of 35 meters;
- (c) to the *inner moraines* of GLACIATION IV, the terraces at levels of 18–32 meters.

These altitudes in meters (18–60) are calculated above the present stream or river level (*thalweg actuel*) and in the broad valleys, farther down stream than declivities, often very steep, of cones of glacial transition. From these terrace altitudes and moraines Depéret makes the following generalization: “*A chaque glaciation correspond donc une valeur différente du creusement de la vallée des cours d’eaux issus des glaciers de cette période.*” To each glaciation corresponds the distinctive level of erosion of the valley produced by the occurrence of water issuing from the glaciers of the corresponding period. There is thus placed in evidence to the glaciologists of the peri-Alpine region a collection of valuable data for the division of the Quaternary Glacial Epoch, which includes the large part of the Pleistocene of Europe. Penck and Brückner in their classic work (1909.1) have given to the *four great phases of extension of the glaciers*, the FOUR GLACIATIONS, the following names, which we may refer to in their descending geologic order:

Postglacial Period

Behind the Würm moraines there occurs a limited number of morainal formations, *moraines stadiaires* [= of stadial or substage rank and not

of stage rank.—Leverett], or morainal stages, which mark the oscillations in the retreat of the glaciers backward to their existing limits, moraines termed by Penck *Neo-Würmian*, following the *recession of Achen*, the *substage of Bühl*, the *substage of Gschnitz*, and the *substage of Daun*. This period is, to some extent, the postglacial of other authors, which may be looked upon as the last interglacial phase, especially if one admits, with Kilian, the short Neo-Würmian glaciation, limited in extent, which preceded the time of continued recession.

Fourth Glacial Period

(IV) This period, with moraines in relation to the gravels of the low terraces, in general 18 to 20 meters above the existing bottom level of the large valleys, equals the *glaciation of Würm* or Würmian, the name derived from a river traversing the plain of Munich, Bavaria. The glaciation of Würm has left the innermost moraines well preserved, with their elements slightly altered, representing the most recent period, with *inner moraines* and a sheet of gravel (*cailloutis*) which [in the Alpine region] is never covered with loess. (See, however, Soergel, 1919.1.)

The *Third Interglaciation* is termed Riss-Würm by Penck.

Third Glacial Period

(III) This period, the moraines of which are related to the gravels of the high terraces ("*graviers de la haute terrasse*"), 30 to 35 meters above the existing bottom level of the large valleys, is termed Riss or Rissian by Penck, the name of an affluent of the Isar River of Germany. The moraines of the *Riss glaciation* lie outside of those of the Würm and in many places fall short of attaining the extent of the moraines of the preceding *Mindel glaciation*. The Riss glaciers rested at the bottom on the surfaces or slopes cleared by the ice of the preceding *Mindel glaciation*. [It is important to note that the outer moraines of the western Alps, particularly in France, regarded as of Riss age by Penck and Brückner, are treated as of Mindelian age by Depéret.]

The *Second Interglaciation* is the Mindel-Riss of Penck.

Second Glacial Period

(II) This period, the moraines of which are related to the recent gravels of the plateaus ("*graviers récents des hauteurs*"), in general 55–60 meters above the actual bottom level of the valleys, is termed Mindel or Mindelian by Penck, a name derived from a tributary of the Danube. The Mindel glaciation had slightly *the greatest extension*; its

moraines are the outermost, the most remote from the central Alpine massif; they indicate the maximum of glacial extension in the Alpine region. Depéret and Mayet observe (Mayet, 1921.2, page 484) that many authors continue to regard the Mindelian moraines, which are the most external on the periphery of the western Alps, as of Rissian age, an erroneous conclusion of Penck and Brückner.

The *First Interglaciation* is the Günz-Mindel of Penck.

First, or most ancient, Glacial Period

(I) This period, the moraines of which are related to the origin of the "*cailloutis des plateaux ou graviers anciens des hauteurs*"—that is, the glacial pebbles of the plateaus, the ancient gravels of the heights, in general 90 to 100 meters above the actual valley bottoms, is termed the Günz or Günzian by Penck, a name derived from another tributary of the Danube between Ulm and Augsburg. The Günz glaciation left but few important traces, represented at the present time by scattered indications which are rarely found beyond the limits of the Alpine valleys. Probably this glaciation was the least extensive.

Conclusion

In concluding this first summary of the observations of Depéret in the peri-Alpine region, we may point out that it is chiefly a corroboration and confirmation of the Penck-Brückner system. The principal differences relate to three points, namely: (1) the connection of the river terrace levels with the marine terrace levels of the Mediterranean; (2) the attribution of Mindelian age to certain moraines termed Rissian in the Penck system; (3) the subdivision of the larger part of the Pleistocene of Europe by means of four outstanding terrace levels, namely, of 90–100 meters (Sicilian), of 55–60 meters (Milazzian), of 28–32 meters (Tyrrhenian), of 18–20 meters (Monastirian), on the theory of marine transgression and regression. In other words, Depéret appears to be the first to connect the peri-Alpine *river* terraces with the Mediterranean *sea* terraces. The second summary is given on page 438 of the present paper.

3. LEVERETT'S COMPARISON OF NORTH AMERICAN AND EUROPEAN GLACIAL DEPOSITS

The reader is referred to the June and July numbers of the *Zeitschrift für Gletscherkunde*, 1910 (Leverett, 1910.1) for a clear exposition of the corresponding position and contemporaneity of the glacial deposits of North

America and Europe by one of America's leading glaciologists, Frank Leverett, of the United States Geological Survey. This observer on two continents chiefly correlates the glacial and interglacial deposits of North America and Europe (1) by means of their corresponding stratigraphic position and relations, (2) by the degree of weathering and erosion, which, although it decreases in amount in passing from the oldest to the youngest series of deposits, is practically the same for any one horizon on both continents.

* The four American drift deposits—Nebraskan, Kansan, Illinoian, and Wisconsin—are thus correlated with the Alpine of Penck and Brückner, Günz, Mindel, Riss, and Würm, respectively. These together correspond to the I, II, III, and IV glaciations, respectively.

Leverett believes that the "Oldest" drift of north Germany, penetrated by well borings near Berlin and near Hamburg, is the product of GLACIATION I (Scanian); at Berlin it is interbedded with fluvioglacial gravel and sand, the outwash deposits of the earliest ice-sheet. He holds that the "Oldest," "Old," "Middle," and "Young" drifts of the north German plain, left at successive periods by the Scandinavian land ice, may be correlated respectively with the several Alpine glaciations; also with the Nebraskan (Jerseyan), Kansan, Illinoian, and Wisconsin stages, or the I, II, III, and IV glaciations.

In the "chalky Boulder-clay" of England, Leverett recognizes the westward extension of the "Old" drift of Germany. The "Middle" drift, however, he does not believe has as yet been identified, though it is not improbable that the Scandinavian land ice in this stage extended across the North Sea to the British Isles.

As to the relative order of magnitude of these glaciations, Leverett believes: (1) that Glaciation I is well represented as far south as Nebraska and New Jersey, but is not extensively exposed in the Alps or in the north German plain, for there it has been concealed in large part by the more extensive later glaciations; (2) that Glaciation II in North America and in Europe was the most extensive of all; (3) that Glaciation III was, in the main, of less extent; (4) that Glaciation IV was still more limited.

The three American interglacial stages are correlated with three in Europe, namely:

First Interglacial Stage, the Aftonian of America = the Günz-Mindel of the Alpine region = the Paludinenbank of north Germany = the Norfolkian of England.

Second Interglacial Stage, the Yarmouth of America = the long Mindel-Riss of the Alpine district = the interglacial deposits of central Russia and perhaps the Rixdorf horizon of Germany.

Third Interglacial Stage, the Sangamon of the United States = the Riss-Würm of the Alpine region and perhaps the Rixdorf horizon of Germany (which is the general view of the German geologists).

By means of their position, texture, and fauna, Leverett also correlates the American "lower loess" and the "main loess" deposits of the Second and Third Interglacial epochs, respectively, with the "lower" and the "upper loess" deposits of northwestern Europe. He observes that the European loess deposits are far less conspicuous, continuous, and extensive than those on the plains of the United States.

4. CORRELATION OF BRITISH AND NORTH EUROPEAN QUATERNARY DEPOSITS OF BROOKS

The reader is referred to the important paper by Brooks (1919.1) on "The correlation of the Quaternary deposits of the British Isles with those of the continent of Europe." While the author holds that no one principle of correlation can be maintained, he adheres strongly to the glacial and interglacial phases which various authors have extended to all the continents. The key to his work lies in north Germany, where Gagel (1913.1) has determined a very definite series of three glacial and two interglacial horizons. Gagel finds no equivalent of the Günzian (I) glaciation, and in the terraces corresponding to the First Interglacial of the Alps he holds that there is no Scandinavian material. These stages are correlated with the Mindel (II), Riss (III), and Würm (IV) glaciations of the Alps. By ordinary stratigraphical and paleontological methods, Brooks traces these beds into Russia, Denmark, and Holland and correlates them with fair certainty with the glacial deposits of eastern England. He establishes a network of cross-correlations between the Alps, the Pyrenees, and intervening glaciated areas by means of the river gravel terraces. He cites, too, the loess deposits and the flint industries of primitive man as means of correlation. All these features are clearly presented in the text as well as in the numerous summaries and tables of correlation. The methods of correlation are similar to those of Penck and Brückner. They are somewhat in agreement, but not precisely in harmony with those of Depéret (1918-1921), which are based primarily on marine formations, marine shorelines, and river terraces at stated elevations.

Quaternary Deposits of the North German Plain (after Brooks, 1919)

Baltic readvance.—Moraines of the Baltic Hohenrücken.

Baltic Interstadial [= Achen recession].—Arctic marine and fresh-water deposits of East and West Prussia.

[GLACIATION IV] *Upper Boulder-clay* [= Würm].—Weathered to a depth of only 1 to 2 meters. This glaciation nowhere overstepped the limits of the preceding one, but was of considerably less extent. Magdalenian culture.

Second Interglacial [= Riss-Würm, 3rd Interglacial].—*Corbicula Duboisiana*. Rixdorf horizon. Mousterian culture.

[GLACIATION III] *Middle Boulder-clay* [Riss].—Weathered to a depth of 10 to 12 meters. This glaciation may have overstepped the limits of the preceding one at a few points. Middle terrace of the rivers. Mousterian culture.

First Interglacial [= Mindel-Riss, 2nd Interglacial].—*Cyprina* clays. Eem beds. Beds with *Paludina diluviana*, *Corbicula fluminalis*, *Bithynia tentaculata*. Acheulean culture.

[GLACIATION II] *Lower Boulder-clay* [= Mindel].—Very deeply weathered. Ice reached its maximum extent at least in the west and southwest and possibly over the whole area. Higher ("chief") terrace of the rivers.

[GLACIATION I Not recognized]

5. NEW CHRONOLOGIC DIVISIONS PROPOSED BY DEPÉRET

Review and Summary of Depéret's proposed chronologic Subdivision of the Quaternary

We have summarized above Depéret's observations on the peri-Alpine region; we may now summarize extensively his proposal of a new chronologic subdivision of the Quaternary based chiefly on a theory of widespread and uniform marine transgression and regression (recession) in western Europe.

Depéret's paper on the chronologic coordination of Quaternary time was published in eight installments in the *Comptes Rendus*, the first appearing March 25, 1918, and successively thereafter until the date of the last, July 26, 1920 (Depéret, 1918.1–5, 1919.1, 1920.1,2). This was followed by a short paper (1921.1) giving his conclusions. In his initial paper (Depéret, 1918.1) he remarked:

"The Quaternary or Pleistocene period, although the most recent of geologic time, is still the most obscure and the least definite so far as classification is concerned, in spite of certain interesting proposed syntheses, especially by Boule, J. Geikie, and Penck, and more recently by Haug. This classification has depended sometimes on the study of marine deposits (Stefani, de Lamothe, Gignoux); sometimes (J. Geikie and Penck) on the series of glaciations observed, either in the north of Europe or in the Alpine border valleys, and, finally (Boule), on prehistory combined with the terrestrial Quaternary fauna and glacial phenomena. None of these classifications appears (in his opinion)

		EN]	
H. F. O., 1922.	Eastern England.	North Europe.	Archeological periods.
		Atlantic period.	Iron.
		Pre-glacial period.	Late neolithic and bronze.
	Submerged forest.	Glacial period and Atlantic period.	Neolithic.
		Post-glacial period and Atlantic period.	Early neolithic.
	Arctic peat bed of Holmpton.	Terrace. [= Last IV] Glaciation by Baltic	Magdalenian. Solutrean.
[= Third Interglaciation.]	Temperate peat of Holderness.	Glacial with <i>Paludicola duboisiana</i> . The same series.	Younger Mousterian.
[= III GLACIATION.]	Arctic bed of Hoxne. Hessle boulder-clay.	[= III] Glacial terrace. Glaciation by Scandinavian ice.	Older Mousterian. Acheulean.
[= Second Interglaciation.]	Temperate lacustrine beds of Hoxne. Marine gravels of Holderness, March, and Clacton.	Glacial of <i>Paludicola diluviana</i> and <i>Hippicula fluminalis</i> . The same.	Chellean.
[= II GLACIATION.]	Chalky boulder - clay and purple clay. Holderness. Yarmouth marine sands, etc. North Sea drift. Arctic freshwater beds.	[= II] Glacial terrace. Glaciation by Scandinavian ice.	
	Cromer forest bed.	Glacial stage.	

NOTE.—In this table (Leverett, 1910.1), or the "Vorletzte glaciation" relates with the "Chalky boulder-clay" of Engverett.

TABLE II

CORRELATION QUATERNARY OF GREAT BRITAIN (BROOKS, 1919.1, PAGE 326) [WITH MODIFICATIONS BY H. F. OSBORN]

H. F. O., 1922.	Eastern England.	Thames Valley.	South coast and south Wales.	Northwest England.	Scotland.	North Europe.	Archeological periods.
				Upper peat.	Corrie glaciers. Upper peat.	Sub-Atlantic period.	Iron.
				Upper forest bed.	Upper forest bed.	Subboreal period.	Late neolithic and bronze.
	Submerged forest.	Buried channel.	Pine forest of Dorset. Submerged forest.	Formby and Leasowe beds and Shirdley hill sand.	Peat. 25-foot beach.	<i>Litorina</i> period and Atlantic period.	Neolithic.
				Lower peat and forest bed.	Peat.	<i>Ancylus</i> period and Boreal period.	Early neolithic.
	Arctic peat bed of Holmpton.	Low terrace.	Possibly upper head.	Arctic peat bed of Pemines.	Small valley glaciers. 50-foot beach. Arctic peat bed.	Low terrace. Third [= Last IV] glaciation by Baltic ice.	Magdalenian. Solutrean.
[= Third Interglaciation.]	Temperate peat of Holderness.	Erosion.			Lower forest layer and peat.	Interglacial with <i>Palu- dina duboisiana</i> . Skaerumede series.	Younger Mousterian.
[= III GLACIATION.]	Arctic bed of Hoxne. Hessle boulder-clay.	Arctic beds of Lea val- ley. "Warp and trail." Middle terrace.	Boulder-clay of Gower. etc. "Head." Raised beach of Sel- sey and Brighton.	Upper boulder-clay. Midglacial sands. Lower boulder-clay.	Large valley glaciers. 100-foot beach. Upper boulder-clay.	[= III] Middle terrace. Second glaciation by Scandinavian ice.	Older Mousterian. Acheulean.
[Second Interglaciation.]	Temperate lacustrine beds of Hoxne. Marine gravels of Hol- derness, March, and Clacton.	Erosion. 130-foot and 100-foot terraces.	Temperate mammalian fauna of Gower. Sands, as with temper- ate fauna at Selsey and elsewhere. End of older raised beach period.	Temperate beds of Lindall, etc.	[2nd] Interglacial beds of Redhill, Kilmaun, etc., and possibly Cleongart and Clava.	Interglacial of <i>Palu- dina diluviana</i> and <i>Corbicula fluminalis</i> . Eem beds.	Chellean.
[= II GLACIATION.]	Chalky boulder - clay and purple clay of Holderness. Yarmouth marine sands, etc. North Sea drift. Arctic freshwater bed.	Chalky boulder-clay.	Boulder-clay of Pen- coed. Older raised beach.	Isolated occurrences of ancient red boul- der-clay.	Older boulder-clay.	[= II] Chief terrace. First glaciation by Scandinavian ice.	
	Cromer forest bed.					Tegelen stage.	

NOTE.—In this table Brooks, following Gagel (1913.1), has overlooked the "Middle drift" = Glacial III of Leverett's paper (Leverett, 1910.1), or the "Vorletzte glaciation" of Kellhack. The drift in northern Europe above the Eem beds and *Paludina diluviana* beds probably correlates with the "Chalky boulder-clay" of England. The drift below these north German interglacial beds seems not to have extended into England.—LEVERETT.

to have solved the problem in its entirety—a complex problem, in which it is necessary to interweave at one time (1) the chronology of marine deposits, (2) the phenomena of valley trenching and the formation of alluvial terraces, (3) the glacial phenomena, (4) the succession of terrestrial animal faunas, and (5) the facts of human paleontology and prehistoric archeology.”

Depéret concludes that, in making a choice between these diverse criteria, he finds himself logically obliged to apply to the Quaternary the method of classification which has prevailed for all the other geologic epochs, namely, of giving *primary weight* to the characters furnished by the ancient marine shorelines (*lignes de rivage*) and their contained invertebrate fossils, making due allowance for the fact that certain species of invertebrates, ancient and modern, live well below the surface of the sea.

He selects the *Mediterranean* as the most thoroughly studied, from the point of view of Quaternary movements and deposits, and refers to earlier work of the Italian geologists (Seguenza, Stefani) and more recent work of Gignoux in determining the terminal stage of the Upper Pliocene as the *Calabrian*. He makes as the first stage of the post-Pliocene, or true Quaternary, the Sicilian, a term which in some of his earlier writings he applied to the Upper Pliocene (compare Osborn, 1910.1, page 305, after Depéret).

De Lamothe (1899.1, 1901.1, 1911.1, 1916.1, 1918.1) has established on the shores of Algeria and Tunis a series of shorelines (*lignes de rivage*), arranged in descending levels, which correspond with advancing geologic time, as follows:

Continental Shoreline Levels of the West Mediterranean, African Coast, de Lamothe		
Pleistocene or Quaternary.	18-20 meters	[= Monastirian Stage—Depéret, Monastir, Tunis.
	28-30 meters	[= Tyrrhenian Stage—Issel, <i>Strombus</i> horizon.
	55-60 meters	[= Milazzian Stage—Depéret, Milazzo, northern Sicily.
	90-100 meters	[= Sicilian Stage—Döderlein, Palermo, Sicily.
? Pliocene.	148 meters	= Ancient marine shorelines, Algeria and Tunis, North Africa.
	204 meters.	
	265 meters.	
	325 meters.	

Depéret’s interpretation (1918.1) is that, while the most elevated of these marine deposits should be attributed to the end of the Pliocene, there is no doubt that the last four shorelines (namely, 100 meters, 60 meters, 30 meters, 18 meters) belong to the Quaternary. Depéret says

that "de Lamothe makes an effort to show that each of these shorelines is the result of a lowering of the sealevel or *movement negative*, followed by a *movement positive*, or elevation of the sea"; in other words, a *regressive movement*, followed by a *transgressive one*. Furthermore, each shoreline observed is supplemented by a series of marine and alluvial sediments which were deposited during the transgressive phase.

Depéret and Gignoux trace these four Quaternary shorelines observed by de Lamothe on the African coast along the Sicilian, Italian, and French coasts, Gignoux (1913.1) making the generalization that the whole western Mediterranean basin exhibits stratigraphic and paleontologic characters of four Quaternary marine stages, with decreasing levels of 90–100 meters, 55–60 meters, 30 meters, and 15–18 meters, thus constituting four distinct stratigraphic units, each corresponding to a complete sedimentation cycle on a shoreline of a determined level. On this primary basis Depéret divides the marine Quaternary of the western Mediterranean into four *étages* resting on the Upper Pliocene, as follows:

Post-Monastirian Stage.—Mediterranean shorelines raised to present level, with a temporary halt at the height of 6 to 8 meters, of which numerous traces appear on the French coast, but insufficient to constitute a distinct stratigraphic unit.

- (4) Monastirian Stage, Depéret.—Corresponding to shoreline of 18–20 meters, named for the city of Monastir, Tunis, which is situated on an extensive plateau belonging to this horizon, with fossiliferous beds of great richness (278 species cited by de Lamothe). Traced to Algero-Tunisian coast and possibly to Sicily. Marked climatic difference between the faunas of the European and African coasts.
- (3) Tyrrhenian Stage, Issel.—Corresponding to 28–30 meter shoreline, distinguished as the *Strombus bubonius* zone of the whole circumference of the Mediterranean. Warm invertebrate fauna with subtropical affinities, some species of which still exist in the Canaries and on the African-Atlantic coast.
- (2) Milazzian Stage, Depéret.—Shoreline of 55–60 meters. Named after the peninsula of Milazzo, northern coast of Sicily. Warm fauna described by Gignoux, with persistent Pliocene species. Temperature warmer than the modern Mediterranean, but less warm than the succeeding *Strombus* seas of the Tyrrhenian Stage. Traced along the Sicilian and Italian coasts.
- (1) Sicilian Stage, Döderlein.—A shoreline of 90–100 meters, typified in the old gulf or Conque d'Or of Palermo—a preserved sea-bottom containing a fauna with maximum frequency of species of temperate and polar Atlantic seas—for example, *Cyprina islandica*, etcetera. Traceable into Sicily, Calabria, Italy, and on the French and north African coasts.

Calabrian. Upper Pliocene, with a prevailing Pliocene fauna, many species of which become extinct in the overlying Sicilian Stage.

Tracing these four shorelines beyond the Mediterranean to the Atlantic coast, Depéret remarks (1918.2) that observers have hitherto noted the height of the locality of marine fossil beds without looking for the *altitude of the corresponding shoreline*, which in many instances is *far above* the fossil beds. Four corresponding shorelines, however, are determinable on the Atlantic coast—Gibraltar, Portugal, Morocco, Senegal, and Angola—from observations of Depéret, Choffat, Dollfus, Dereims, Chudeau, and Chautard, which in Depéret's opinion may be coordinated respectively with the

- (4) Monastirian Stage (18–20 meters),
- (3) Tyrrhenian Stage (28–30 meters),
- (2) Milazzian Stage (55–60 meters),
- (1) Sicilian Stage (90–100 meters).

Observations extended northward along the French Atlantic coast convince Depéret (1918.3) that as far north as Brittany the Quaternary sea also occupied successively four shorelines of 90–100 meters, 55–60 meters, 30–35 meters, and 18–20 meters above the present shoreline, which coincide exactly with his Sicilian, Milazzian, Tyrrhenian, and Monastirian shorelines of the Mediterranean. This northern coast also shows traces of old shores characterized by shells at some quite low levels—the first at 7–10 meters, the second at 18–20 meters, above the present ocean level. It will appear natural to attach the 20-meter level, as noted above, to the Monastirian Stage. At that time the geography of our coasts was nearly identical to the present geography.

Marine Quaternary of the French and English Atlantic Coasts

Depéret continues (1918.4) that along the French and British coasts of the English Channel are observed marine deposits 6 meters above the present mean sealevel, containing *Buccinum grænlandicum*, but the altitude of the corresponding shoreline is not determined.

In the valley of the Somme, where the Quaternary sea penetrated to Abbeville (the locality famous for the earliest Chellean industry), are observed the marine depositions of Menchecourt and Mautort (Prestwich, 1860, and subsequently described by Charles Lyell, d'Ault du Mesnil, Ladrière, Rutot, and Commont, famous archeologists). The base of the marine deposit of *Menchecourt* is only 5 meters above the high waters of the Somme; its summit about 11 meters; above which are clays with a minimum altitude of 15 meters, constituting a terrace of the 18–20-meter level belonging to Depéret's *Monastirian Stage*, with which the author correlates the cold marine terrestrial fauna described below. In these beds occur the fluvial species *Corbicula fluminalis*, surviving from the

Pliocene and early Quaternary, intermingled with a cold, north temperate modern fauna (29 species). Higher up, at Menchecourt, is a strip containing the warm *Elephas antiquus* fauna and rude Chellean tools.

Depéret does not recognize his Tyrrhenian Stage (28–30 meters) at this point (elsewhere correlated with the warm *Elephas antiquus* fauna), but nearer to the mouth of the Somme, at Saint-Valery, he recognizes with de Lamothe sandy plateaus of the 30-meter level, of marine origin, which he considers incontestable evidence of the *Tyrrhenian Stage*, for the first time recognized on the French Atlantic coast. North of the Somme the marine deposits of 11-meter altitude (ancient shoreline of 20 meters) indicate, according to de Lamothe and Depéret, the 18–20-meter Monastirian shoreline. Still farther north, on the French coast of the English Channel, are recognized again the 30–35-meter shoreline of the Tyrrhenian Stage, the 55–60-meter shoreline of the Milazzian Stage, and even the 100-meter shoreline of the Sicilian Stage. Thence de Lamothe and Depéret trace above Havre a precise correlation with the 100-meter shoreline of the Sicilian Stage.

Crossing the Channel to the southern English coasts, Depéret (1918.5) traces many shorelines of 0–20 meters, from the Isle of Wight to Plymouth and along the coast of Devon to the south near Brighton and Bristol, recognizing throughout the higher of these marine levels (18–20 meters) as the Monastirian shoreline, with deposits in which the absence of Mediterranean and Lusitanian forms denotes waters a little colder than those of the English Channel at present, although not containing truly arctic forms.

Most interesting to the paleontologist are the Sussex and Hampshire coasts (studied by Godwin Austen, Prestwich, Bell, and Reid), where a typical coastal plain yields mammals of the *Elephas primigenius* cold fauna and marine Quaternary deposits near Portsmouth, with a constant altitude of 30–33 meters. He concludes:

“If one adds the presence of *Elephas antiquus* in the deposit of Selsey it is seen that all these facts are in accord to indicate, on the south coast of England at the epoch of the 30–33-meter shoreline, a sea with a temperature warmer than the present sea, thus agreeing well with the introduction in the Mediterranean of the *Strombus bubonius* warm fauna of the Tyrrhenian Stage.”

Elsewhere—for example, on the north coast of the Isle of Wight—he recognizes the 52–60-meter Milazzian Stage and the 100-meter Sicilian Stage.

Land Connections across the British Channel

Coordination.—At this important point it would seem desirable to abstract Depéret more fully (1918.5). It appears interesting to me to

coordinate the entirety of the preceding observations on the two banks of the English Channel and the Pas de Calais in relation to the important question of the union of England with France in the Quaternary epoch and to the opening epoch of the Pas de Calais (that is, channel opposite Calais).

A simple solution, founded on the distribution of the Quaternary marine deposits, follows: One may admit a *quite large junction of France and England during the Sicilian and Milazzian epochs* (= Periods of Glaciation I and II), represented only by a coastal plain at the altitudes of 100 meters and 60 meters. The English Channel was certainly more contracted than today, without having to determine its limits. The *Elephas antiquus* warm fauna and *hippopotami* were thus able to emigrate freely into England.

At the Tyrrhenian epoch (= Period of Glaciation III), the 30-33-meter shoreline is well characterized on the French coast (Saint Valéry), and above all on the English coast (Sussex), with a marine and terrestrial fauna with southern affinities. One may deduce from this that the English Channel formed then a great Atlantic gulf extending at least as far north as the estuary of the Somme, but separated from the North Sea by a quite large isthmus. This conception explains the absence of arctic shells in the Tyrrhenian fauna of the English Channel and a continuation of the exchanges of the terrestrial fauna between England and the continent.

But at the Monastirian epoch (= Period of Glaciation IV) the continuity of the marine deposits of the 20-meter shoreline (and lower lines) reveals to us a geography almost identical with that of the present day, as so perfectly recognized by Briquet. The opening of the Pas de Calais admitted the migration into the English Channel of a colder marine fauna from the North Sea.

Migration of cold land fauna.—But this simple interpretation is marred by the difficulty of explaining the passage into England of the cold land fauna of terrestrial animals of upper Quaternary times. It becomes necessary, therefore, to introduce into the problem a new element, which I have abstractly shown here, that of the phases of marine regression (with the lowering of the shorelines to the level and even below the shore), from which begin each of the four Quaternary stages. These phenomena of regression, so sharply marked in the Mediterranean, are geologic events too important not to be found in other seas. In fact, the position of the levels of the present shore of estuarine beds of the Tyrrhenian of Sussex, as well as the Sicilian forest bed of Cromer, not to speak of the submerged forest and submarine valleys of more recent age, show us typical examples of it.

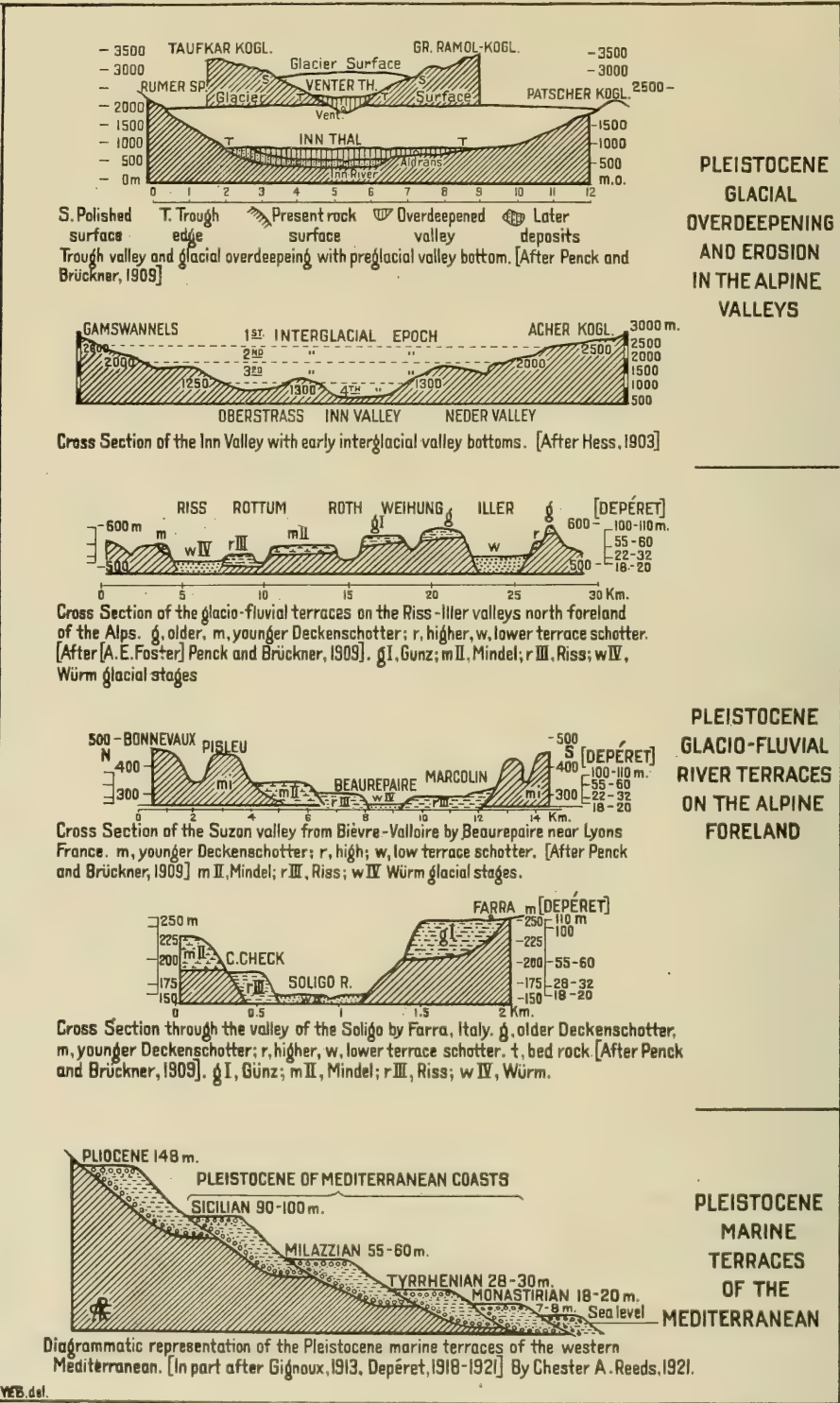


FIGURE 2.—Graphic Presentation of the Relation of the Pleistocene glacial Phenomena of the Alps to the River and Marine Terraces of Europe

One should then admit, in order to explain the passing of the fauna of cold mammals into England, the existence of a phase of marine regression [H. F. O., ? coastal elevation] which might have taken place, say, at the beginning of the Monastirian, or perhaps at the end of the Monastirian. It is this last point of view that Barrois (1897.1) has adopted in establishing the distribution of clay (limon) in Brittany; this clay (limon), which is later than the "elevated banks," extends on the littoral islands contained inside the curve of 25 meters of marine depth. Barrois admits that in this epoch the English Channel was transformed into a fluvial valley, with the waters flowing to the west. In this valley, and on one side or the other of the Pas de Calais, gravels were deposited which contain remains of the mammoth and of *Rhinoceros tichorhinus*, now dredged from the bottom of the English Channel and the Dogger Bank in the North Sea. Then a very recent new marine transgression [H. F. O., ? coastal depression] intervened causing the isthmus of the Pas de Calais to disappear definitely.

Relation of terraces to moraines.—Depéret follows with a consideration of the northern coasts of France. After reviewing (1919.1) the work of Geikie, Penck and Brückner, and his own observations in the Alps and Pyrenees (as tabulated on page 414), and after considering the evidence afforded by *moraines* and *river terraces*, he gives the following generalization:

I intend above all to establish a constant relation between the frontal moraines of each glaciation and the relative altitude of the fluvial terraces which came from them. The external moraines are related to the 55–60-meter terraces; the intermediary moraines to the 30-meter terraces; the internal moraines to the 18–20-meter terraces. Following each glaciation is a distinct erosion period of the valleys by great floods of water issuing from the glaciers.

This moraine-terrace relation establishes a general principle applicable to the glaciers emptying into the Atlantic and Mediterranean valleys, which Depéret also extends to the great glaciers of the north of Europe, observing that this precise method of *comparative determination of Quaternary glaciers by the altitude of the corresponding fluvial terraces* was noted by Penck and Brückner in their magnificent work on the glaciation of the Alps, but that the constant relation of the terraces and respective elevations were not established by them. [In figure 2, Doctor Reeds has assembled a series of cross-section profiles to illustrate the relations of the various Alpine glaciations to the river terraces of the Alpine foreland and the marine terraces of the Mediterranean.] Taking

account of the relative altitudes of the terraces in the eastern and central Alps, Depéret maintains that

IV GLACIATION.—The Würmian frontal moraines are in constant relation with a low terrace destitute of loess (*Niederterrasse* of Penck), the altitude of which maintains itself generally between 15–20 meters above the existing great river courses.

III GLACIATION.—The Rissian frontal moraines continue by terraces (*Hochterrasse* of Penck), which dominate by a score of meters the Würmian, and attain a relative altitude of 30–35 meters.

II GLACIATION.—The Mindelian terminal moraines east of the Alps are related to terraces (*jüngerer Deckenschotter* of Penck) 20–25 meters higher than the Rissian terraces—that is to say, with a relative altitude of 50–60 meters.

I GLACIATION.—The Günzian moraines, while infrequent, give rise to terraces (*älterer Deckenschotter* of Penck) whose relative altitudes attain in the most frequent cases 90–100 meters above the existing rivers.

The external moraines in the region of Lyons, with their terraces of 55–60 meters, in his opinion are not the Rissian, as Penck and Brückner supposed, but the Mindelian. Thus the maximum extension of Alpine glaciers on the eastern and western sides of the Alps corresponds to the Mindelian (II) and not to the Rissian (III) glaciation. It is only in the central part of the Alps that the Rhine glacier of Rissian (III) times may have extended farther north than the preceding Mindelian (II) glaciation.

Synchronism of Alpine and Scandinavian advances.—Depéret then proceeds to a comparison of the Alpine glaciations with the Scandinavian, and remarks that it appears quite natural to admit that the maximum extension of the Alpine glaciers (Mindelian) coincides with the maximum advance of the Scandinavian glaciers ("old Drift," or Saxonian). Thus the Rissian (III) of the Alps corresponds to the "upper Drift," or Polonian (III), of the plains of the north of England, and it is necessary for us to find the equivalent of the Würmian (IV) in the local glaciers of the Scottish highlands and in the Baltic moraines (Mecklenburgian, IV). Finally, it seems logical to see in the Scanian (I) glaciation the counterpart of the Günzian (I) of the Alps. He adopts a parallelism (see Table I above), beginning with the fourfold division of Geikie in 1914 and ending with his introduction of the fourfold altitudes of fluvial terraces corresponding to each glaciation. He concludes: *It remains to be shown that the Quaternary shorelines of the north of*

Europe are also in perfect harmony with this classification of the Glacial Period and of the fluvial terraces.

Depéret's Correlation of northern Moraines and Mediterranean Quaternary Shorelines

In the north of Europe there took place repeated invasions of great sheets of land ice, spreading from the Scandinavian and Scottish mountains, advancing and eroding the basins of the Irish, the North, and the Baltic seas, and stretching out over the British Isles, the German plains, and the plains of Poland and Russia. The sea was excluded from these basins by masses of ice many thousands of meters in thickness, and it was only during intervals between glaciations that the sea was able to return and form marine and interglacial deposits. The subsequent return of the glaciers would cause erosion and the more or less complete destruction of the marine deposits of the preceding interglacial phase. Thus comparison with the undisturbed marine deposits of the Mediterranean borders is rendered very difficult. Nevertheless, certain surviving marine deposits of the north of Europe may be correlated with those of the Mediterranean, as follows:

- | | |
|---|--|
| 1. <i>Sicilian Stage</i> of the Mediterranean = <i>Cromerian Stage</i> of the North Sea | |
| characterized by species of the north imported by cold Atlantic currents (see above). | basin and Baltic, with its regressive marine phase at the beginning (Forest Bed of Norfolk) and its transgressive terminal phase (deep-water clays with <i>Yoldia myalis</i> and <i>arctica</i>). Many arctic species (187) imported by the deep currents of the glacial ocean. |

1. *Sicilian Stage, Depéret, 1920.*—On the east coast of the North Sea and along the German-Baltic coast Depéret recognizes marine faunal beds of Sicilian-Cromerian age, covering a ground moraine of (I) Scanian-Günzian age, so that they occupy an interglacial position. Depéret (1920.1, 1920.2) similarly reviews the glacial and interglacial deposits of Great Britain, and on the basis of the eustatic movements of sealevel concludes:

“The following table summarizes the coordination that I believe I shall be able to propose between the Quaternary formations of the British Isles and those of the Mediterranean. If this coordination is accepted, the whole Quaternary history of the British Isles may be explained without being obliged to invoke the least movement of the earth, either epirogenic or even isostatic.”

TABLE III

BRITISH AND MEDITERRANEAN CORRELATION, DEPÉRET, 1920 (WITH INTERLINEATIONS BY THE PRESENT AUTHORS, CHIEFLY FROM DEPÉRET'S TEXT)

Mediterranean shorelines	Quaternary formations of the British Isles	British shorelines
Postglacial.	25-foot marine terrace, Scotland, submerged forest, peat; modern marine fauna; early Neolithic. [This ranges in altitude from about 35 feet above sea-level down to and slightly below sealevel (W. B. Wright, 1914.1).]	8 meters
Monastirian Stage, 15-20 meters.	50-foot marine terrace, Scotland, English Channel; many British species and some arctic. IV GLACIATION = Mecklenburgian-Würmian, restricted to highlands; great valley glaciers, some piedmont; terminal moraines strong and fresh.	15-20 meters 20 meters
Tyrrhenian Stage, 30-33 meters.	100-foot marine terrace, Scotland, not yet recognized in England and Ireland, on "upper Boulder-clay" and in fiords. Extreme arctic fauna, <i>Pecten grænlandicus</i> , <i>Yoldia arctica</i> , <i>Tellina myopsis</i> . III GLACIATION = Polonian-Rissian, not so extensive as II, Saxonian - Mindelian. "upper Boulder-clay." Interglacial marine gravels of Holderness, Yarmouth, Speeton, etcetera: 30-meter shoreline of Sussex. Ireland: high shell beds = reworked erratic deposits of Saxonian stage. Holderness: modern British marine fauna, 61 species, with temperate forms <i>Cytherea chinoe</i> , <i>Venus gallina</i> , and fresh-water shell of warm climate, <i>Corbicula fluminalis</i> , estuarine; near Yarmouth, fauna (80 species) largely British, some Mediterranean forms: <i>Turritella incrustata</i> , <i>Limopsis pygmaea</i> , <i>Cardita corbis</i> , <i>Cytherea rudis</i> ; a more temperate sea than the modern English sea. Scotland: sand, gravels, clays, marine shells. Interglacial marine deposits with temperate fauna = Tyrrhenian Stage of Mediterranean.	33 meters 33 meters

Mediterranean shorelines	Quaternary formations of the British Isles	British shorelines
Milazzian Stage, 55-60 meters.	II GLACIATION = Saxonian-Mindelien.... Maximum glaciation, "lower Boulder-clay" north of Thames-Bristol channel, near coasts; fragmentary shells of arctic species left by glaciers; marine deposits unknown.	Unknown
Pre-Milazzian regression.	Preglacial banks of Sewerby, Gower, and Ireland, with modern marine shells; warm land fauna in river beds and coastal grottoes.	4-8 meters
Sicilian Stage (= Cromerian), 90-100 meters.	<i>Yoldia myalis</i> shales of Norfolk; marine transgression; sea becomes deep; sand, clay, ooze; many arctic shells. Top of <i>Yoldia myalis</i> stratum, 10 meters above mean sealevel. At top deep-sea ooze, incomplete, due to ice invasion; boulder-clay; angular blocks of clay and marine sands intercalated erratically—Bridlington crag—from bottom of North Sea, from 50 to 80 meters; fauna 87 per cent arctic = Sicilian, 100 meters.	90-100 meters probably
Pre-Sicilian regression.	Forest Bed of Norfolk, estuarine..... General temperate character of the fauna of mollusks and vertebrates. [Weybourn and Chillesford Crag = ? Period of I GLACIATION—Scanian-Günzian.] [Red Crag, Pliocene = Astian Stage of north Italy.]	6-8 meters

Notes by Osborn, 1921.—The above table presents a number of inter-lineations in square brackets which will serve to connect Depéret's coordination of 1920 with the preceding and succeeding text of this article. Following Geikie, the generally accepted correlation of the beginning of Quaternary time in East Anglia, Norfolk (Osborn, 1915.1, pages 252-264), is as follows:

- Forest Bed of Cromer* = First Interglacial Time.—Warm, north temperate mammal fauna, also tundra fauna.
- Weybourn Crag* (Essex) and *Chillesford Crag* (Norfolk) = Time of I GLACIATION.—First northern and arctic marine Mollusca on British east coast.
- Red Crag* = Upper Pliocene.—Warm continental fauna similar to that of the Astian stage, northern Italy, closing with evidences of a colder climate.

Beneath the Forest Bed there has been discovered recently by J. Reid Moir a bed of giant flints of human manufacture, an industry which

may be termed *Cromerian*. In the heart of the Red Crag there has also been discovered by Moir another human industry, which may be termed *Foxhallian*. In the sub-Red Crag detritus there have also been found flints of human manufacture. The relation of these extremely ancient industries to the geologic table is exhibited in the final correlation table of this article, figure 13.

Depéret's Interpretation and Correlation of the British Quaternary

Reviewing the researches of British geologists, Depéret interprets the British Quaternary succession as follows:

[=I GLACIATION, Scanian, and *First Interglacial Stage*, Norfolkian of Geikie]

Sicilian-Cromerian Stage (in part).—First phase. The Quaternary begins on the Norfolk coast between the early Pleistocene Weybourn and Chillesford Crags and the Forest Bed of Cromer. Between two fresh-water beds is the fluvio-marine or estuarine Forest Bed proper, composed of trunks and roots of trees that drifted into an estuary—the fluvio-marine shells of the Forest Bed are of modern North Sea littoral species—*Cardium edule*, *Mytilus edulis*, *Donax vittatus*, *Tellina balthica*, *Mya truncata*, *Purpura lapillus*, *Littorina littorea*. Not far distant occurs one arctic species, *Scalaria grœnlandica*, which indicates the approach of polar currents in spite of the generally temperate fauna. The Forest Bed was then at sealevel, indicating that an important phase of marine recession and continental elevation occurred toward the beginning of Sicilian time.

Second phase. There followed a continental depression and marine invasion, probably to the 90–100 meter line, with the appearance of many arctic shells, *Yoldia myalis* and *Astarta borealis*, intermingled with a majority of surviving Forest Bed species. The *Yoldia* of this species may occur at a depth of 300 meters. Depéret concludes that although it is difficult to determine the exact altitude of the shoreline at this point, there is nothing to oppose the idea that it had attained the normal altitude of the Sicilian—say, to 100 meters.

Both the *Yoldia myalis* bed and the underlying Forest Bed may be compared with the Sicilian Stage in the Mediterranean, also characterized by species imported by cold Atlantic currents. In brief, Depéret correlates the coldest marine fauna of the British coast with the 100-meter level and the cold Mediterranean fauna of the Sicilian Stage. To the same stage may be attributed the angular blocks of clay and the

marine sands, both erratically intercalated in the clay *at the base* of the "lower Boulder-clay" of the coast of Holderness, Yorkshire. These erratic blocks contain a fauna more arctic than that of any other English Quaternary deposit; of 100 species, 87 are related to modern arctic types. There are deposits of the same age in Ayrshire, on the east coast of the North Sea, and on the German-Baltic coast, *Yoldia arctica* and *Astarta borealis* being characteristic arctic species.

Final phase. The *terminal phase* is one of continental depression and marine elevation (deep-water clays with *Yoldia myalis* and *Y. arctica*). Following the deposits of the *Yoldia myalis* beds, there was a marked marine recession and continental elevation, the shorelines lowering themselves to the present level on the coast of Yorkshire, of Scotland and Ireland. Thus a *very low shoreline*, preceded the maximum glacial extension on the British Isles (II Saxonian-Mindelien). The marine fauna of these beds resembled closely the modern British fauna. At Sewerby, above the marine shore, are deposits of continental rivers containing a warm fauna little different from that of the Forest Bed (*Elephas antiquus*, *Rhinoceros merckii*, *Hippopotamus amphibius*, *Hyæna crocuta*), but lacking [Osborn] the cold mammal fauna of the Forest Bed (*Elephas primigenius*, *Ovibos moschatus*, etcetera).

[= II GLACIATION, Saxonian of Geikie]

Milazzian Stage of Depéret.—The great Scandinavian glacier (II Mindelian-Saxonian) now covered the British Isles, except the region south of the Thames and the Bristol Channel. It deposited the "*lower Boulder-clay*," locally known as Red, Basement-clay, and Chalky Boulder-clay; the "*lower Till*" of Scotland; in the Boulder-clay, especially near the coast, are arctic species of marine shells, probably brought with floating ice as erratics, but there are no contemporaneous marine deposits.

[= *Second Interglacial Stage*, Tyrolian of Geikie, post-Saxonian]

The climate warmed and the great Saxonian glacier retired. To this phase belong the sands and gravels of variable thickness, intercalated between the "lower Boulder-clay" and the "upper Boulder-clay," and containing marine shells, arctic and British. These shell deposits, formerly regarded (Geikie, 1914.1) as proofs of submergence of the British Isles to a depth of nearly 500 meters, have more recently been shown to be displaced fossils contained in morainal detritus and erosion, since they include certain Pliocene mollusks evidently derived from Pliocene rocks.

Thus the British theory of deep submergence in Second Interglacial times has been abandoned.

[= III GLACIATION, Polonian of Geikie] (Polonian = IV GLACIATION by Leverett)

After the temperate phase [= Second Interglacial] the Polonian-Rissian glaciation advances anew over the British Isles, but less to the south than the preceding Saxonian. In Ireland and Wales the advance of the two glaciers was not very different, or at least their limits have not been sharply traced, but in the center and the east of England the limit of the "recent Drift" marks a sinuous line which lies a long distance north of the limit of the "old Drift"; the "upper Boulder-clay" of GLACIATION III (Polonian), strewn with moraines and drumlins, is in striking topographic contrast with the monotonous surfaces of the "lower Boulder-clay," leveled and cut by deep valleys. The deposits of this glaciation are the "internal moraines," the "recent Drift," the "upper Till," the "upper Boulder-clay."

The Polonian glacier receded again to Scandinavia, leaving the country bare and admitting the North Sea again to the British coast. In Scotland the marine terrace of 100 feet, with an extreme arctic fauna (*Pecten groenlandicus*, *Yoldia arctica*, *Tellina myopsis*), is superposed on the "upper Till" of GLACIATION III (Polonian). This is attributed [rightly] to a local isostatic elevation due to melting during GLACIATION III (Polonian). They are considered by Leverett the correlatives of moraines of the last or fourth glaciation in Germany, outside of Geikie's Mecklenburgian. [Leverett (1901.1) examined moraines in Vale of York and elsewhere in northern England which are here classed as Polonian, and they now seem to him too fresh to be so classed, but are likely to be moraines of the Fourth glacial stage.]

[= *Third Interglacial Stage*, Dürntenian of Geikie]

Tyrrhenian Stage of Depéret.—"The entirety of the interglacial marine deposits of temperate fauna corresponds, without doubt, to the Tyrrhenian Stage of the Mediterranean with a shoreline of identical altitude (33 meters, maximum)" (Depéret, 1920.2). As the great Scandinavian glacier again retired, the North Sea again approached the English coast, and at Holderness (Prestwich, Reid) have been determined [Second Interglacial] gravels and argillaceous marine sands intercalated between the "lower Boulder-clay" and the "upper Boulder-clay." Beds corresponding with the shoreline of 33 meters (100 feet) have been traced

by Reid for nearly 100 kilometers on the east coast of Britain, from the Flamborough Cape to the south of the Humber Estuary. The 33-meter terrace of Scotland maintains a constant altitude and is regarded by Depéret as a *terminal phase* of the Tyrrhenian shorelines. The marine fauna (61 species) is that of the modern British seas, but with some elements of a more temperate climate (*Cytherea chione*, *Venus gallina*) and even of fresh-water shells of a warm climate (*Corbicula fluminalis*) abundant near Kelsey and Croxton; the same species occur in deposits of the 30-meter shoreline of Sussex, associated with a still more temperate marine fauna. Similar 30-meter deposits are found at Speeton (near Scarborough) below the "upper Boulder-clay." Near Yarmouth, Norfolk, are "middle sands," intercalated between "upper" and "lower Boulder-clays," at a maximum altitude of 33 meters, containing (Wood and Harmer) a fauna of eighty species, mostly British, partly Mediterranean (*Turritella incrassata*, *Limopsis pygmaea*, *Cardita corbis*, *Cytherea rudis*), denoting a sea *more temperate* than the modern English seas.

[= IV GLACIATION, Mecklenburgian of Geikie]

The final glacial phase in Great Britain is limited to certain Highland massifs, the Hebrides, the Grampians, the Lake district, Wales, and Ireland. It is an epoch of great valley glaciers, often joined together at their outlets on the plain. The strength and freshness of the terminal moraines recall those of the Baltic moraines of the Mecklenburgian glacier and of the Würmian moraines of the Alpine glacier. The original attribution by Geikie of these local glaciers to a later time than the 33-meter (100-foot) beach is confirmed by the observations of Wright (1914.1, page 368) on the western coasts of Scotland where the Loch Carron glacier reaches the 20-meter shore. Similar levels in other parts of northern Scotland convince Depéret that the local glaciation of the Highlands corresponds to the 20-meter shoreline of his *Monastirian Stage*. Traced around the Scottish coast, this 15–20-meter shoreline is compared by Depéret with the Monastirian shoreline which he has recognized on all the coasts of the English Channel, the Atlantic, and the Mediterranean. [Leverett is now of the opinion that Geikie's "Mecklenburgian" does not include the earlier moraines of the last glaciation to the south of (outside) the Baltic moraine. Penck as well as the Prussian geologists think the Baltic moraine is not the limit of the last glaciation.]

Post-Monastirian Stage.—After a marine recessive period, giving place to the formation of peats and submerged forests, the sea advances again and the last marine terrace of 25 feet, containing a modern marine fauna,

is noted by Depéret on all the Atlantic and Mediterranean coasts. In Scotland, according to Wright, it ranges from 35 feet down to sealevel (1914.1, page 382). Associated with a modern marine fauna there have been found in Scotland the first human stone implements of the beginning of Neolithic time,⁶ analogous to those of Denmark and Scandinavia.

Summary of Depéret's conclusions, geology and archeology (1921.1).— (1) In Depéret's opinion, we should abandon the terms "middle," "lower," and "upper" Quaternary and adopt a fourfold stratigraphic subdivision founded on marine transgression and regression stages. (2) Each of the stages which he proposes (*Sicilian, Milazzian, Tyrrhenian, and Monastirian*) constitutes a complete sedimentary cycle readily observed, corresponding to shorelines falling gradually from 90–100 meters to 55–60 meters, to 28–32 meters, to 18–20 meters below the present sealevel, in addition to the still lower shoreline of 7–8 meters. (3) Depéret has endeavored to demonstrate that identical shorelines are found on the Atlantic, African, and European coasts of western Europe. (4) These displacements of baselevel are in concordance with corresponding displacements of streamlevel, for the streams erode their beds when the sea is depressed and fill their beds when the sea mounts. (5) For this reason the formation of the four fluvial terraces corresponds to the shorelines above mentioned, as noted by various authors, along the Isser, the Moselle, the Rhine, the Rhone, the Danube, the Somme, the Loire, the Seine, the Garonne, the Nive, the Belgian rivers, and the rivers of Morocco. (6) Whichever theoretic explanation is adopted, the elevation of the continent or the lowering of the sealevel, the *constancy* and the *equidistance* of these terraces impress themselves as facts of general observation and serve as a basis of rational classification of Quaternary time. (7) At least four terraces relate themselves in an intimate manner with the four Quaternary glaciations of the Alps and the north of Europe, namely, the terrace of 100 meters is very probably related in origin with the moraines of I (the Günz); the terrace of 55–60 meters is related with the moraines of II (the Mindel); the terrace of 30 meters is related with the moraines of III (the Riss); the terrace of 18–20 meters is related with the moraines of IV (the Würm). (8) The

⁶ Bearing on this subject, the present authors note, for example, the report of A. Henderson Bishop, F. S. A. Scot., on "An Oransay shell-mound—A Scottish pre-Neolithic site," from which they quote as follows: "The object of this paper . . . is to demonstrate from the shell-mounds of Oransay the existence of human habitation on or about the line of the 25–30 feet beach at a time when the sea had not permanently retired from that level, and, incidentally, to reveal the Azilian nature of the culture indicated in the occupation, and thus to correlate it directly with that of the Oban caves."

interglacial phases correspond with the lower portion of each of these terraces in the fluvio-glacial regions. (9) The arrival of Chellean man does not correspond to lower Quaternary time, but dates solely from the Tyrrhenian epoch of the terrace of 30 meters. In the preceding epochs of Sicilian terraces (90–100 meters) and Milazzian terraces (55–60 meters) no industrial or other evidence of the existence of man in Europe has thus far been found, leaving aside the question of eoliths (Depéret, 1921.1, page 126). The *Chellean* industry corresponds with the *base* of the 30-meter terrace. The *Acheulean* industry occurs higher up on the 30-meter terrace. The *Mousterian* industry occurs on the 18–20-meter terrace. The *Aurignacian* industry occurs in the upper part of the 18–20-meter terrace. In the final *Magdalenian* industry the valleys were nearly down to their actual present level.

6. POSTGLACIAL GEOCHRONOLOGY OF SWEDEN, FINLAND, AND NORTH AMERICA OF DE GEER (REVISED BY DR. E. ANTEVS)⁷

Brückner, in the *Zeitschrift für Gletscherkunde*, July, 1921, pages 39–57 (Brückner, 1921.1), discusses the work of De Geer and his junior colleagues. This review is of special interest to American students of this problem, since Brückner was joint author with Penck of the epoch-making work “Die Alpen im Eiszeitalter,” 1901–1909 (Penck and Brückner, 1909.1).

De Geer's Method, which permits the determination of the Postglacial epoch in absolute measurements of time and a geochronology of the retreat of the land ice, was developed in the vicinity of Stockholm. It consists of the examination, measurement, and coordination of the seasonal layers of banded clay of glacial origin which were deposited in the Baltic and in various lakes that covered extensive parts of Sweden during the retreat of the land ice of the Fourth, or last, Glaciation. Many of these deposits now appear as land above the level of the Baltic.

Each annual layer consists of two deposits—a lower, summer layer, which is thicker, of more sandy material; an upper, winter layer, which is thinner, of darker color and of very fine clay, deposited in the following winter. In various exposures numerous annual layers are superimposed one above another. In recording them the thickness of each seasonal layer is marked on the margin of a *long strip of paper*. As the character of the weather during the melting period varied from year to year, these fluctuations are reflected in the varying thicknesses of the annual deposits.

⁷ In February, 1922, Dr. E. Anteys read the portion of this manuscript dealing with the De Geer chronology and made a few suggestions and additions which have been incorporated in the present paper.

In order to be able to express in a convenient manner the synchrony of the banded clay layers of one station with those of another, at a considerable distance, the record of each station is thrown into the form of a curve, with the number of annual layers exposed in each section entered on the abscissa and the thickness of each indicated as ordinates. The thick deposits have high points in the curve and the thin layers low ones. By superimposing the curves of each of the stations, one to two kilometers apart, on a line over 800 kilometers long, it was readily noted that a specific layer could be easily traced a distance of 50 or more kilometers.

The annual layers during deposition stood in close relation to the border of the land ice. The material of which they consist was carried to the lakes by numerous subglacial rivers which flowed through ice-tunnels. On entering the lake the coarse material was dropped in the shape of a delta, while the finer, consisting of sand and clay, was deployed fanwise and deposited at varying distances, the sand first and the fine particles composing the clay still farther out. With increasing distance from the mouths of the subglacial rivers at the ice-borders, each varve (seasonal layer) shows a decrease in its thickness and size of grain. In the summer, when the glacial water was profuse, a great quantity of sand as well as clay reached the lake, while in winter, when there was no melting, or hardly any, only clay was deposited.

Where the border of the land ice was stationary, one layer was deposited on top of the other; when, however, the ice retreated northward, a portion of the glacial territory became free of ice and a varve was immediately deposited on it and to the southward over previously existing layers. Thus, with the continual retreat of the ice, each subsequent varve transgressed toward the north. Its northern boundary indicates the position of the ice-border during its formation. The following up of the northern boundary of each varve permits, therefore, the determination of the gradual retreat of the ice from year to year. It was thus necessary to determine from numerous clay profiles the northern boundary of each varve. This De Geer has done with the assistance of a number of university students.

With the retreat of the ice, the subglacial rivers shifted in a northerly direction, and with them the delta of coarse material formed at the border of the ice and the lake. Many deltas in this manner have been extended into a long ridge called an *Os*.

The retreat of the ice was accomplished in the summer; in the winter, however, there was a stoppage or short advance. During these advances, in some cases low, narrow ridges of glacial material, sometimes not even a meter high, were formed as winter moraines. The above-described

relations between the varve clays, the *O_s* formation, and the annual terminal moraines have been demonstrated by tracing them in numerous places.

In this manner De Geer was able to trace the retreat of the land ice from year to year through Sweden. The retreat was accomplished very gradually in Scania and Bleking, about 75 meters a year. Farther northward it increased to 100 meters or a little more, up to the great central Swedish moraines. These indicate distinct adverse climatic conditions. Then the retreat set in more powerfully; it was accomplished with considerable speed and regularity and only occasionally was interrupted by a stoppage or a small advance. The record of the retreat fluctuates from 100 to 300 meters or more a year.

Let us briefly summarize the results of De Geer and his students. The retreat of the ice during Daniglacial time (see figure 3)—that is, from the terminal moraines representing the maximum advance of the Fourth, or Mecklenburgian, Glaciation over the north German lowland and Denmark to the moraines across middle Scania, the southernmost peninsula of Sweden—is unknown. Allowing 50,000 years from the present to the first maximum advance of the Fourth (Würm) Glaciation (chart by Soergel and Reeds, figure 11), it is estimated to have taken 33,500 years. The retreat in Sweden during the Gotiglacial epoch—that is, from the terminal moraines in middle Scania to the southern border of the great Fennoscandian moraines south of Stockholm—took about 3,000 years; the Finiglacial time—that is, the retreat from the southernmost of the Fennoscandian moraines to the parting of the land ice in south Jamtland—represents 2,000 years. This totals 5,000 years. The upbuilding of the Fennoscandian moraine zone, which is included as the initial part of the Finiglacial epoch, has been determined by Sauramo (1918.1) in Finland to be 225 years for the outer moraine, 252 years for the inner moraine, and 183 years for the intervening territory—a total of 660 years.

From the annual layers deposited in the valley of the river Ångermanälven, Antevs says that Lidén has determined the postglacial time as 8,500 years in length. Postglacial time to Swedish geologists is the time since the division of the land ice into two parts at Ragunda, in north Sweden. This gives 13,500 years for the determined retreat of the land ice of Glaciation IV across Sweden from central Scania to the present small ice-caps in north central Sweden. To this we might add 3,000 years as an estimate of the time for the early undetermined portion of the Gotiglacial stage in south Scania—that is, 16,500 years from the supposed beginning of the Gotiglacial Stage to A. D. 1900.

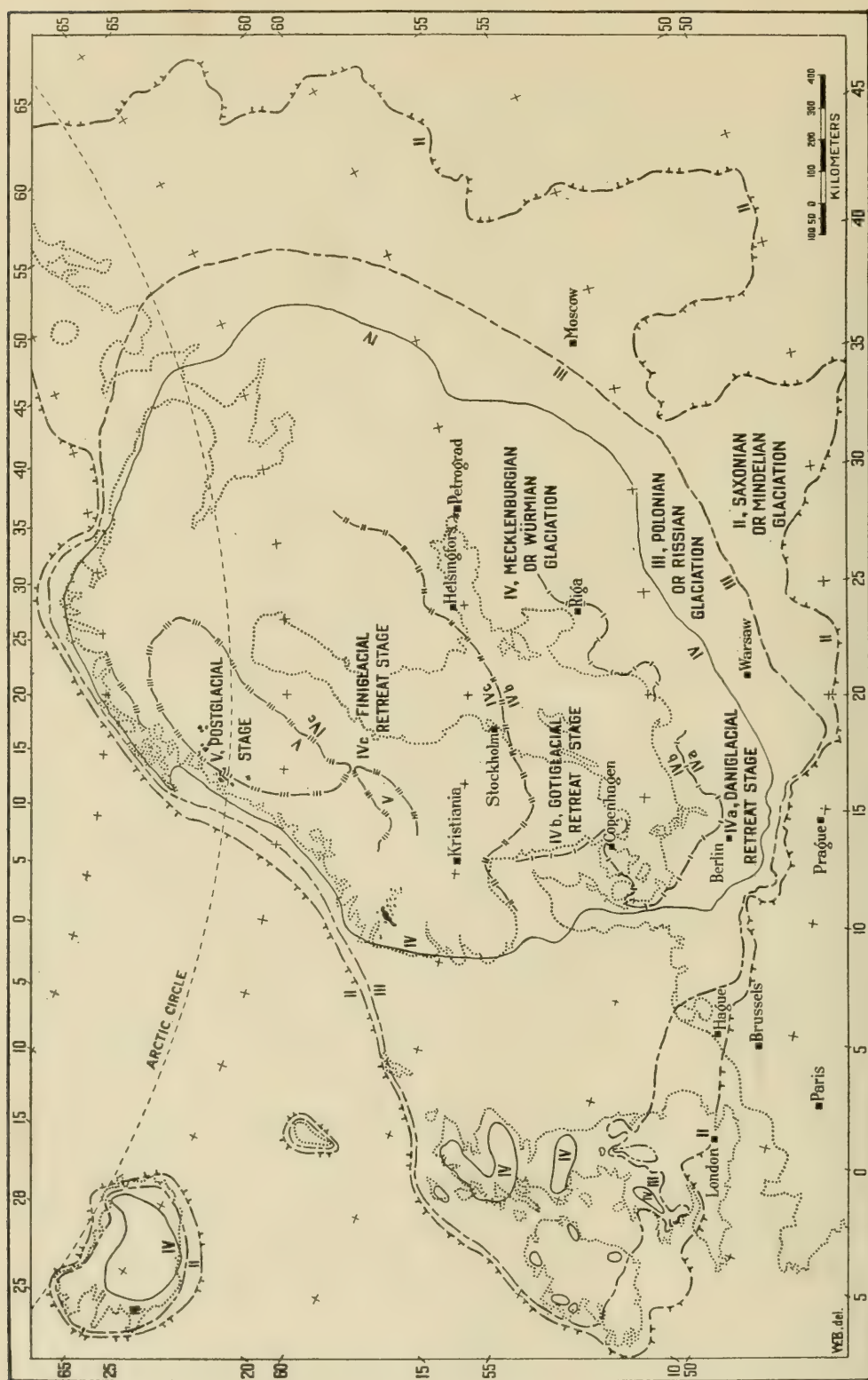


FIGURE 3.—Map of North European Glaciation

There are shown thereon the II, III, and IV major advances, the Daniglacial, Gotiglacial, and Finiglacial retreat stages of the IV, and V, the Postglacial; the present glaciers in solid black (after De Geer, Gelkie, Leverett, Penck, and Munthe), by Chester A. Reeds, 1921.

Varve chronology. G. De Geer and R. Lidén, 1921.	Glacial stage De Geer, 1911 (modified).	Flora. von Post, 1918.	Fauna. Osborn, 1921.
0 (1900 A. D.)		beech, spruce forests.	
—1000	Recent.		
—2000			
—3000			
—4000	Postglacial (Lake Ragunda and Angermanälven recesses).	oak and other forest trees.	Stag.
—5000			
—6000			
—7000			Moose.
—8000	$\pm$ 0 of Swedish geologists, —8500 years.		
—9000			
—10000			
—11000	Finiglacial.	Lappas flora, with pine and birch.	Reindeer.
—12000			
—13000	Gotiglacial (Ice sheet from central Scania, central Germany to the Fennoscandian moraines.)		
—14000			
—15000			
—16000			
—17000	Daniglacial.		
—18000			

The De Geer geochronology and the contemporaneous paleogeography of Sweden have been correlated by Reeds and Antevs in Table IV.

In 1914, De Geer undertook to extend his method to Finland. From this suggestion resulted the great work of Sauramo, "Geochronological studies of the late glacial time in south Finland" (1918.1). This study gave valuable results which correspond perfectly with those in Sweden.

In the autumn of 1920 De Geer, with Lidén and Antevs, visited North America to determine how far the Swedish time scale could be used on the retreat of the North American land ice.

A short preliminary paper was published by De Geer (1921.1) in which he tentatively correlates the varves of American localities—Woodsville, Waterbury, Wells River, Essex Junction, Spanish River, Espanola Haileybury, and Dickson Creek—with certain segments of the previously determined varve geochronology in Sweden. According to this investigation, the varves representing the years—1556 to + 297 of the Swedish time scale are 74 to 89 per cent in accord with those of America, while 26 to 13 per cent are local developments. As this is a preliminary statement, it is probable that when the data collected by De Geer and his assistants are fully worked up the results may or may not be in accord with this tentative correlation.

Brückner (1921.1, page 54) concludes:

"Thus the geochronology of North America for the late glacial period seems to conform with that of Scandinavia. However, I must admit that from the meteorological standpoint such a far-reaching parallelization of the fluctuations of the weather from one year to the other, in Sweden and North America, is surprising. . . . Therefore, although I absolutely agree with De Geer's conclusions concerning Sweden and Finland, I can not help making some reservations as to the parallelizing of the banded clay layers in the United States. This in nowise means that in general I do not consider it probable that there should be an analogous course of the retreat of the ice in Scandinavia and in America; *vice versa*, based on my researches about climatic oscillations within a period of 35 years, I have always maintained that the whole process of the glaciation in northern Europe and North America is uniform as to time, evenness, and manner."

II. CORRELATION OF THE TIME DIVISIONS WITH HUMAN INDUSTRIES

1. CORRELATION OF THE PENCK-BRÜCKNER TIME DIVISIONS WITH HUMAN INDUSTRIES

As early as 1903 Penck (Penck and Brückner, 1909.1) essayed to correlate these Alpine glacial and interglacial extensions and recessions with the human flint industries, including the far-distant *Chellean* industry in the valleys of the Somme and the Marne, the *Mousterian* and

TABLE IV
CORRELATION OF THE DE GEER GEOCHRONOLOGY WITH THE PALEOGEOGRAPHY OF SWEDEN
By Chester A. Reeds and E. Antevs, February, 1922

Varve chronology. G. De Geer and R. Lidén, 1921.	Glacial stages. De Geer, 1914 (modified).	Ice-front.	Changes of level in Sweden (Bohuslän). Antevs, 1921.	Baltic. Munthe, 1910 (modified).	Climate. Sernander, 1910.	Flora. von Post, 1918.	Fauna. Osborn, 1921.	
0 (1900 A. D.)	Recent.	At present small ice-caps on high plateaus, Norway and Sweden.	Present level reached about —2600.	Mya time.	Subatlantic cold, moist.	Beech, spruce forests.		
—1000				Linnæa time.	(Drop in temperature).			
—2000								
—3000								
—4000	Postglacial (Lake Ragunda and River Angermanälven.)		Elevation, —4000.	Littorina time.	Subboreal, warm, dry.	Oak and other forest trees.	Stag.	
—5000			Submergence, —5000.		Atlantic, warm, moist.			
—6000			Elevation, —6000.		Boreal, warm, dry.			
—7000			Submergence, —7000.					
—8000	± 0 of Swedish geologists, —8500 years.	Ice parted into two parts in Jämtland, —8500.	Elevation, —8000.	Ancylus time (fresh-water inland sea).			Moose.	
—9000			Submergence, —9000.					
—10000			Elevation, —10000.					(—10000± Drainage of the Baltic ice-lake at Mt. Billingen).
—11000			Submergence, —11000.					
—12000	Finiglacial.	Ice-front at Fennoscandian moraines, near Stockholm, —10500 to —10000.	Elevation, —12000.	South Baltic Ice-lakes and fresh-water inland seas.	(Subarctic).	Dryas flora, with pine and birch.	Reindeer.	
—13000								
—14000								
—15000								
—16000	Gotiglacial (Ice-retreat from central Scania, central Denmark, and northern Germany to the Fennoscandian moraines.)	Ice leaves central Scania,—13500.	(Depressed to marine limit 141 meters when relieved of the ice.)		Arctic.			
—17000								
—18000								
	Daniglacial.	Ice-retreat from outermost limit of GLACIATION IV, over Denmark and northern Germany; readvance to the extreme limit of the Gotiglacial stage. Time unknown (—50000 to —16500±).						

Solutrean industries chiefly in the basin of the Dordogne River, the *Magdalenian* industries, which are richly represented in the Dordogne region and the Pyrenees and sparingly on the borders of the Würm glacier in the peri-Alpine region, as shown below:

TABLE V

GLACIAL AND ARCHEOLOGICAL CORRELATION OF PENCK, 1903 (PENCK AND BRÜCKNER, 1909.1)

Postglacial:	
(d) Stage of Daun.	
(c) Stage of Gschnitz.	
(b) Stage of Bühl.....	Magdalenian.
(a) Oscillation of Achen.	
IV GLACIATION, or <i>Würmian</i> .	
Third Interglacial, Riss-Würm:	
(b) Steppe fauna.....	Solutrean.
(a) Warm fauna.....	Mousterian, warm.
III GLACIATION, or <i>Rissian</i>	
Second Interglacial, Mindel-Riss.....	Chellean.
II GLACIATION, or <i>Mindelian</i> .	
First Interglacial, Günz-Mindel.	
I GLACIATION, or <i>Günzian</i> .	

Two of Penck's correlations appear to be confirmed today, namely:

Postglacial time: Bühl stage=Magdalenian industry.

Second Interglacial time: Mindel-Riss=Chellean industry.

Three of Penck's correlations have since been modified, as follows:

Postglacial time: Steppe faunal stage=Solutrean industry.

IV GLACIAL time: Tundra faunal stage=Mousterian industry.

Third Interglacial time: Final warm fauna=pre-Mousterian industry.

From 1909 Penck's peri-Alpine time standards (based on glacial and interglacial phenomena) have been generally employed by European glaciologists and archeologists with gradually increasing precision, as shown in the correlations of Hugo Obermaier (1909-1921), who began his career as a geologist in the first decade of this century, as field assistant to Professor Penck, before entering the field of archeology. As an original and highly trained observer in both fields, Obermaier's conclusions as expressed, first, in his technical papers of 1909 (1909.1), and then summarized in his popular works of 1912 and 1916 (1912.1, 1916.1), merit the greatest consideration. In the latter, benefiting by his observations in Spain, he works out, in a noteworthy manner, the glaciated Pyrenees region.

TABLE VI
GLACIAL AND ARCHEOLOGICAL CORRELATIONS OF H. OBERMAIER, 1909-1922^s

	1909	1922
Postglacial	Magdalenian Solutrean Aurignacian	Bühl advance Achen retreat
IV Glacial Epoch.....	Monsterian	{ Solutrean. Aurignacian (late). Aurignacian (early). Monsterian (late).
Third Interglacial Period:		
(b) Steppe fauna.....	Monsterian (early)	{ Monsterian (early). Achenlean (late).
(a) Warm fauna.....	Achenlean Chellean	{ Achenlean (early). Chellean (late). ?
III Glacial Epoch.....		Steppe phase
Second Interglacial Period.....		Chellean (early)? Pre-Chellean.
II Glacial Epoch.....		{ No indications of man's presence.
First Interglacial Period.....		
I Glacial Epoch.....		

^s This is taken from Hugo Obermaier's "El Hombre Fósil" (1916.1), and the revised text will be issued as "Fossil Man in Spain," by the Hispanic Society of America, during the coming year, 1923.

A very important difference is that Obermaier now agrees with Penck (1909.1) and shifts the beginning of the Chellean industry (that is, pre-Chellean) back to *Second Interglacial* time. The same conclusion is expressed by Mayet in his table of 1919 (compare Mayet, 1921.2, page 486):

TABLE VII	
GLACIAL AND ARCHEOLOGIC CORRELATION OF LUCIEN MAYET, 1919 ⁹	
	NEOLITHIC.
	Azilian.
(Glaciation, neo-Würmian).....	Magdalenian (late).
Postglacial	Magdalenian.
(Fourth period of regression of glaciers.)	Magdalenian (early) } Solutrean.
[IV] Glaciation of Würm.....	Aurignacian (late) }
(Fourth period of extension of glaciers.)	Aurignacian.
[Third] Interglaciation, Riss-Würm.	Aurignacian (early).
(Third period of regression of glaciers.)	Mousterian (late).
	Mousterian.
	Mousterian (early).
	Close of Acheulean.
[III] Glaciation of Riss.....	Acheulean.
(Third period of extension of glaciers.)	Close of Chellean.
[Second] Interglaciation, Mindel- Riss	Chellean.
(Second period of regression of glaciers.)	pre-Chellean?
[II] Glaciation of Mindel.]	
[First Interglaciation. Günz-Mindel.]	
[Glaciation of Günz.]	

The most recent (1921) correlation is that of the eminent paleontologist of the Paris Museum, Marcellin Boule (1921.1), who, adhering to his opinions of 1888 (1888.1), (1) places the I Glaciation in Pliocene time, (2) unites the II and III Glaciations and the Second and Third Interglaciations of other authors into a single glacial and interglacial cycle (Boule, 1921.1, pages 48, 49) and correlates the human stages as follows:

⁹ Enseignement de l'année 1919-1920 à la Faculté des Sciences de Lyon.

TERTIAIRE. PLIOCÈNE. QUATERNAIRE. PLEISTOCÈNE.

TABLE VIII

GLACIAL AND ARCHEOLOGICAL CORRELATION AFTER BOULE, 1921

Dépôts supérieurs des grottes. Partie supérieure du loess. Climat froid, sec, régime de steppes ou de toundras. <i>Phase Post-glaciaire</i>	Faune de steppes. époque du RENNE. Faune de toundras.	MAGDALÉNIEN. SOLUTRÉEN. AURIGNACIEN. HOMO SAPIENS fossilis. Race de CHANCELADE. Race de Cro-MAGNON. Race de GRIMALDI.
Grands dépôts de remplissage des cavernes. Loess. Alluvions des bas niveaux seulement.	Époque du MAMMOUTH.	HOMO NEANDERTHALENSIS.
DERNIERE GRANDE PHASE GLACIAIRE	<i>Elephas primigenius.</i> <i>Rhinoceros tichorhinus,</i> etcetera.	HOMO DAWSONI.
Climat froid, humide.	Époque de L'HIPPOTAME.	HOMO HEIDELBERGENSIS.
Vieilles alluvions des cavernes. Alluvions des terrasses moyennes et inférieures. Tufs calcaires.	<i>Hippopotamus amphibius.</i> <i>Elephas antiquus.</i> <i>Rhinoceros Mercki.</i> Époque de L'ÉLÉPHANT MÉRIDIONAL.	HOMO
<i>Grand Phase Interglaciaire</i>	CHELLÉEN.	HEIDELBERGENSIS.
Climat doux.	L'AVANT-DERNIERE GRANDE PHASE GLACIAIRE	HOMO
Alluvions des plateaux.	<i>Grande Phase Interglaciaire.</i>	HOMO
GRANDE PHASE GLACIAIRE	<i>Elephas meridionalis.</i> <i>Rhinoceros etruscus.</i> <i>Equus Stenonis.</i>	HOMO

Figure 4 is a synthesis of the observations of Commont on the River Somme, archeologic and geologic. The diagram is a synthesis of the evidence assembled by Commont through years of work (1908-1914) and examinations made in a great many localities; it demonstrates a sequence of eight main geologic depositions, each with characteristic fossils and industries, more or less uniform, on terraces I, II, III, and IV, as indicated in the diagram. The "gravels" at the bottom contain a middle Second Interglacial fauna and late Chellean implements, and the "brick earth" at the top contains Neolithic implements above and Paleolithic implements below. Immediately below the "brick earth" appears the "newer loess," which contains *Elephas primigenius*, *Rhinoceros tichorhinus*, and the reindeer *Rangifer tarandus*, a cold fauna of the Fourth Glaciation. This horizon seems to correlate with Depéret's Monastirian Stage, while the "older loess" appearing below contains an Acheulean industry with *Cyrena fluminalis* and *Belgrandia marginata*, fluvial or brackish water species, indicate estuarine conditions in the Somme Valley produced by slight subsidence of the area. This subsidence, according to Commont, terminated the Chellean epoch in the Somme Valley. As noted in figure 13, the Chellean is regarded as Second Interglacial.

The diagram incorporates for each terrace the corresponding deposits, human industries, and fauna as worked out by Commont (1910.1) for the localities Saint Acheul, Montières, and Abbeville. The first two are close together, while the third is somewhat distant. At Abbeville the basal terrace IV is below present sealevel. Thus the tabulation represents a correlation of data from the three stations, Saint Acheul, Montières, and Abbeville, subtended beneath the Saint Acheul profile sketch, which serves as a key to the relation of the terraces and their deposits. The chances for error are less with a threefold correlation than with a single section, for in three sections there is a fuller representation of the beds, cultures, and fauna.

High level fluvial gravels (fourth terrace [I] of Saint Acheul) have not furnished remains of human industry at any point of the valley. Pre-chelléen (coups de poing à talon réservé, à peine ébauchés accompagnés de nombreux petits outils), niveau de 40 mètres, faune: ancienne d'Abbeville. "Those of the *third terrace* [II] enclose at Abbeville a fauna of Pliocene affinity and have given at Amiens numerous remains of a very rough industry, but undoubtedly fashioned by man and affirming his existence at the beginning of the Pleistocene."

Chelléen, proprement dit (coups de poing allongés): fiers de Saint-Acheul et nombreux petits outils: racloirs, grattoirs, perçoirs, etc., niveau de 30 mètres [III].

Chelléen évolué (coups de poing triangulaires très finement taillés: type de Montières) niveau de 10 mètres [IV]. Contemporaneous with *Elephas antiquus* and *Hippopotamus*. *Elephas antiquus* and *Hippopotamus* in the lower gravels of the basal terrace of the left bank of the Somme at Montières and Saint Roch (altitude, 22 meters), associated with coups de poing of late Chellean type, prove that at the end of the Chellean epoch the valley was already nearly completely carved (+ 20 meters at Montières and — 5 meters at Abbeville).

Late Chellean age of base of 10-meter terrace.—It is very important to note that the synthesis of Commont is based on his theory that the entire valley of the Somme (which, unlike the peri-Alpine rivers, was not fed from glacial sources) was excavated *previous to the deposition of the lowest gravels, which contain, at the base of the 10-meter level, late Chellean implements; also the remains of Elephas antiquus and Hippopotamus*; this corresponds in time with the middle of the Second Interglacial Period. It follows that the gravels at the base of the 10-meter terrace, including the bottom of the Somme River bed itself, are more ancient than those of the 10-meter levels in certain other valleys; and this 10-meter terrace is more ancient than the 30-meter terrace in certain other valleys. This renders one cautious in using Depéret's system of terrace levels (especially in application to terraces beyond the peri-Alpine region) for purposes of geosynchronism. This synthetic key to Commont's subdivision of the deposits and of the human industries, also to the climate and the fauna, shows that while the archeologic and paleontologic *succession* is entirely consistent with that observed at many other points, we are compelled to interpret the geologic age of these terraces in a manner quite different from that employed by Depéret, namely, the synchronizing of the terraces by their respective height above sealevel or above the old river bed. In other words, the archeologic and paleontologic evidence in the Somme Valley does not lend support to Depéret's theory as applied to this region.

2. CORRELATION OF THE DEPÉRET AND MAYET TIME DIVISIONS WITH
HUMAN INDUSTRIES

*Correlation: Chellean Industry = Second Interglacial Period = Terraces
of 28-32 Meters*

This correlation by Mayet (1921.1, 1921.2) agrees with Penck's correlation of 1909 (Penck and Brückner, 1909.1), with the observations on the Somme Valley by Commont (1906-1914), and approximately with Obermaier, 1922 (see footnote on page 445). Mayet states (1921.1, page 6) :

"De ce qui précède, on peut conclure que la migration humaine—d'origine encore inconnue—ayant amené nos premiers ancêtres sur notre sol, s'est faite au cours du Tyrrhénien, lors de l'édification de la terrasse de 30 mètres, donc après le maximum d'extension glaciaire en Europe, après la glaciation Mindélienne. Ils sont venus, apportant l'industrie chelléenne, c'est-à-dire une technique déjà perfectionnée de la taille du silex impliquant une longue phase antérieure de différenciation psychique, de culture intellectuelle."



FIGURE 5.—Quarry Section at Chelles-sur-Marne

There is indicated thereon the paleolithic station where Chellean flint implements were first discovered. The uneven line between the Chellean and Acheulean beds represents an intervening interval of erosion. The Acheulean-Mousterian succession is regular and unbroken. According to recent correlation :

Mousterian industry, beginning in *Third Interglacial Time*.

Acheulean industry, beginning in *III GLACIAL Time* (Riss).

Chellean (and pre-Chellean) industry, beginning in *Second Interglacial Time*.

Summing up this evidence, Mayet observes (opposite citation, page 4) :

"(1) At the base of the terraces of 30 meters [=Tyrrhenian stage of Depéret] we find the Chellean industry with amygdaloid utensils and warm fauna associated. An erosion of the upper part of this terrace of 30 meters is often observed, so that the front is worn away into debris at the foot of the terrace. This secondary erosion is the cause of frequent errors of calculation in terrace altitudes and consequently of the age of the terrace formation itself." (See figure 4 for cross-section of the terraces on the River Somme at Saint Acheul, northern France.)

Chelles on the Marne River (figure 5).—Here the ravine-like erosion of the gravels constituting the terrace of 30 meters and the terrace of 20 meters is displayed with remarkable clearness. The light-colored ancient sands of the upper terrace contain the Chellean industry. The deeper-colored, more recent sands of the lower terrace contain the Mousterian industry. In the photographs of the quarry sections of Chelles, especially those taken in the ballastière Trioux, the strongly undulated line of unconformity marking the contact between the light Chellean sands below and the dark Mousterian sands above is very apparent.

Like other flint industries, the Chellean represents a prolonged evolution, divisible into three stages (compare Osborn, 1915.2), as follows:

Late Chellean.—First appearance of the oval *coups de poing*; also of long-pointed *coups de poing*, in most cases flaked on both sides, with little of the crust of the flint nodule adhering and the edges still unsymmetrical.

Late Chellean.—Well advanced Chellean industry at Torralba, Spain (Obermaier, 1921). Fauna includes the same African mammals (hippopotamus, straight-tusked elephant, Merck's rhinoceros) as that of the early Chellean, with a mingling of the forest and meadow fauna of western Europe, including the new mammoth (*Elephas trogontherii*).

Early Chellean.—First appearance of the amygdaloid *coups de poing*, almond shaped. All flint implements unsymmetrical and with sinuous edges. Small implements, including scrapers (*racloirs*), planes (*grattoirs*), borers (*perçoirs*).

Early Chellean.—Occurs on the 30-foot terrace at Chelles, on the Somme: at Gray's Thurrock and Ilford, on the Thames. Warm temperate fauna, including the hippopotamus, straight-tusked elephant (*E. antiquus*), Merck's rhinoceros (*R. merckii*), but generally lacking the saber-tooth tiger (*Machærodus*), the Etruscan rhinoceros (*R. etruscus*), and other species of pre-Chellean times.

Pre-Chellean.—Prototypes of *coups de poing* formed of flint nodules, with crust only partially removed. Flint forms partly accidental; retouch limited to the few strokes necessary to give a point or edge to the tool or to allow a firm grasp by the hand (protective retouch). Continued use of chance and accidental forms of flints.

Pre-Chellean.—This rare pre-Chellean industry is found at the base of the gravels of the terrace of 28-30 meters, at St. Acheul on the Somme. The industry also occurs in the *gisement du Champ de Mars*, near Abbeville, on the Somme, in association with the Etruscan rhinoceros (*R. etruscus*), Steno's horse (*E. stenorhinus*), and very numerous specimens of the saber-tooth tiger (*Machairodus*), of the striped hyena (*H. striata*), and of the hippopotamus.

Cergy, in the valley of the Oise, presents an extensive erosion (*décapage poussé très loin*) of the terrace of 30 meters.

Montières-lès-Amiens, on the Somme, exhibits a full series of sections showing a Mousterian industry superposed on gravels spared by the erosion of the terrace of 30 meters and containing flints of Chellean-Acheulean age. This secondary *ravinement* or erosion is frequently observed in the Paris basin. According to Commont (1916.1, page 350):

" . . . L'activité des cours d'eau à cette époque explique que les alluvions déjà déposées antérieurement ont été recouvertes par des alluvions moustériennes les ayant même complètement ravinées et qui ont ainsi mis en contact des industries humaines et des faunes d'âge différent, rendant parfois les recherches difficiles aux préhistoriens et aux géologues."

Mauer, on the Neckar, near Heidelberg (figures 6 and 7), a celebrated formation which contained the lower jaw of *Homo heidelbergensis*, is, according to Depéret, at the base of the terrace of 32 meters. It is covered by a thick deposit of loess. [Leverett is now of the opinion that the height of the terrace on the Neckar should have less weight than the *weathering* in determining its age.]

The *Chellean* industry, with its warm fauna and primitive amygdaloid implements, corresponds to the base of the terrace of 30 meters, or Tyrrhenian, whereas the Acheulean industry, with more advanced amygdaloid implements and mixture of colder and warmer fauna, occurs in the superior portion of the same terrace. This succession is observed in France in the valleys of the Somme (Saint Acheul, Abbeville) and of the Seine (Montreuil, La Celle-sous-Moret); in England in the valleys of the Thames, of the Avon, and of the Ouse; in Belgium in the valleys of the Meuse, of the Haine, and of the Lys; in southern Germany the horizon of Mauer near Heidelberg, with a warm fauna and *Homo heidelbergensis*, occurs at the base of a terrace of 32 meters in the valley of the

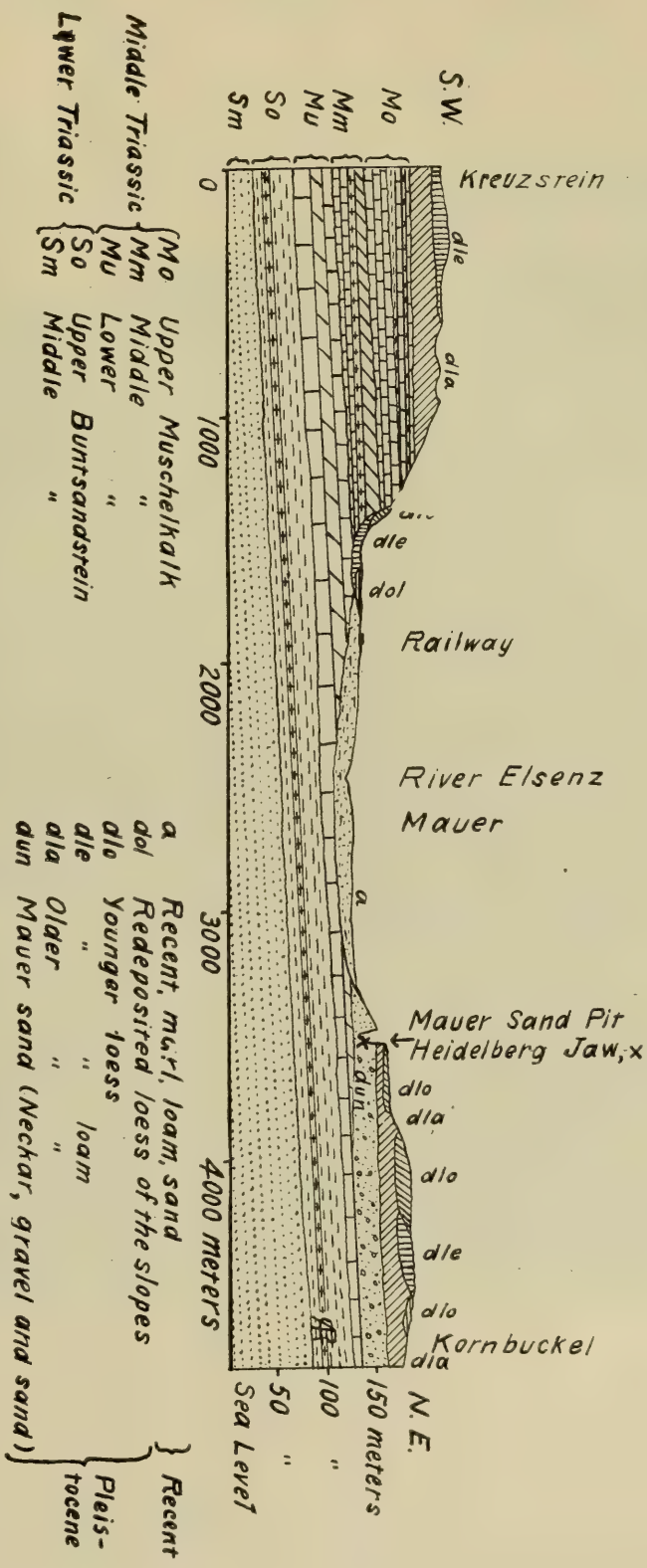


FIGURE 6.—Cross-section of the Valley of the River Elsenz at Mauers, Germany, near Heidelberg. The location of the Mauers sand-pit in which the jaw of *Homo heidelbergensis* was discovered is shown. According to Depéret, the jaw was found at the base of the terrace of 32 meters, the Tertiary Stage. Leverett regards the weathering of more importance than the height of the terrace in determining its age. Osborn and Reeds (figure 13) place the jaw and the basal gravels in which it was found in the First Interglacial Period.

Neckar. Erosion frequently alters the characteristics of the terrace, so that the upper part is presented as debris at the bottom of the terrace (for example, Chelles, Cergy, Billancourt) and has been a frequent cause

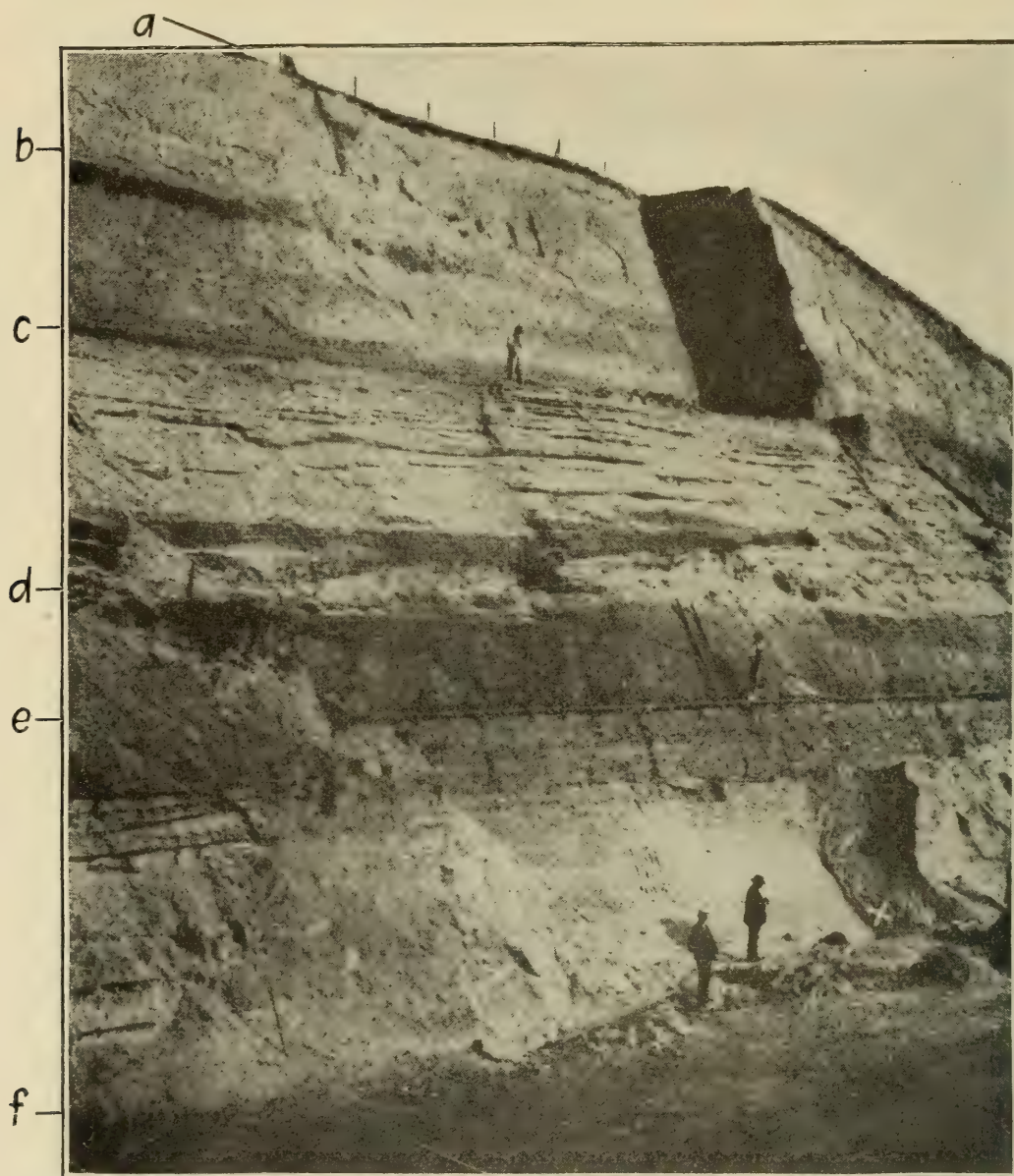


FIGURE 7.—Sand-pit at Mauer, near Heidelberg, the discovery Site of the Jaw of the Heidelberg Man, *Homo heidelbergensis*

After Schoetensack.

a-b—"Newer loess" of the Fourth Glaciation.

b-c—"Older loess" (sandy loess) of the Third Glaciation.

c-d—Mauer Sands and gravels of the Second Interglacial Stage.

d-e—A layer of clay (loess loam?) of the Second Glaciation.

e-f—Mauer Sands and gravels of the First Interglacial Stage.

The white cross (x) indicates the spot at the base of the "sands of Mauer" at which the jaw of Heidelberg man was discovered.

of error in the appreciation of altitudes (Summary by Depéret, 1921.1, page 126).

Correlation: Acheulean Industry = Middle and Upper Portions of Terraces of 28–32 Meters, beginning with close of Glaciation III (Riss) and ending with approach of Glaciation IV (Würm)

This correlation accords with the work of Commont above cited and with Mayet (Mayet, 1921.2).

Like the Chellean, the Acheulean industry (compare Osborn, 1915.2) presents two or three phases, as follows:

Late Acheulean.—Marked evolution of flaked flints—for example, Levallois blades, acme of the *coups de poing* industry; perfected use of the flint cores; improved flake industry, including perfected Levallois blades. Near Levallois, station of Villejuif, south of Paris, Acheulean flints are buried in drifts of loess. Period of close of Acheulean culture; flint workers seeking sheltering cliffs and entrances of the grottoes during cold season of the year.

Early Acheulean.—Flint implements more symmetrical than in the late Chellean. Several varieties of *coups de poing*, mostly of large size, fashioned for industrial use, or in war, or in the chase; also smaller tools, planes, scrapers, borers, knives, and “pointes.” Early Acheulean industry widely distributed in open stations over western Europe.

Cool Acheulean.—Associated with the flora of a cool temperate climate (*tuf de La Cèlle-sous-Moret*); also arid, older or “lower loess” deposits all over northern Europe. Disappearance of the hippopotamus and southern mammoth. Appearance of Neanderthaloid race in Krapina, Croatia.

Warm Acheulean.—Associated with a fauna closely similar to that of late Chellean times. Survival of hippopotami, rhinoceroses, southern mammoths, and straight-tusked elephants as far north as Taubach, near Weimar, Germany. This ancient Thuringian fauna of Taubach, Ehringsdorf, and Achenheim includes also the primitive Neanderthaloid *Homo neanderthalensis* recently described by Virchow (1920.1).

Saint Acheul, Abbeville, Menchecourt, Montières, in the valley of the Somme, all exhibit Acheulean layers overlying the Chellean and sometimes divisible, through the flint evolution, into *early-warm-Acheulean* and *late-cool-Acheulean*, as, for example, on the high terrace of Saint Acheul (figure 8).

La Celle-sous-Moret.—This Acheulean horizon is particularly interesting. A terrace of 30 meters was built up by gravels representing about one-half of its height—that is, elevated 15 meters above the existing

level of the waters of the Seine—and overlaid by a series of tufa layers of a combined thickness of 15 meters, which represent not only tufa inclines (*tuf de pente*), but tufa of the valley bottom, local facies of the Tyrrhenian alluvium of the valley of the Seine. In the middle portion

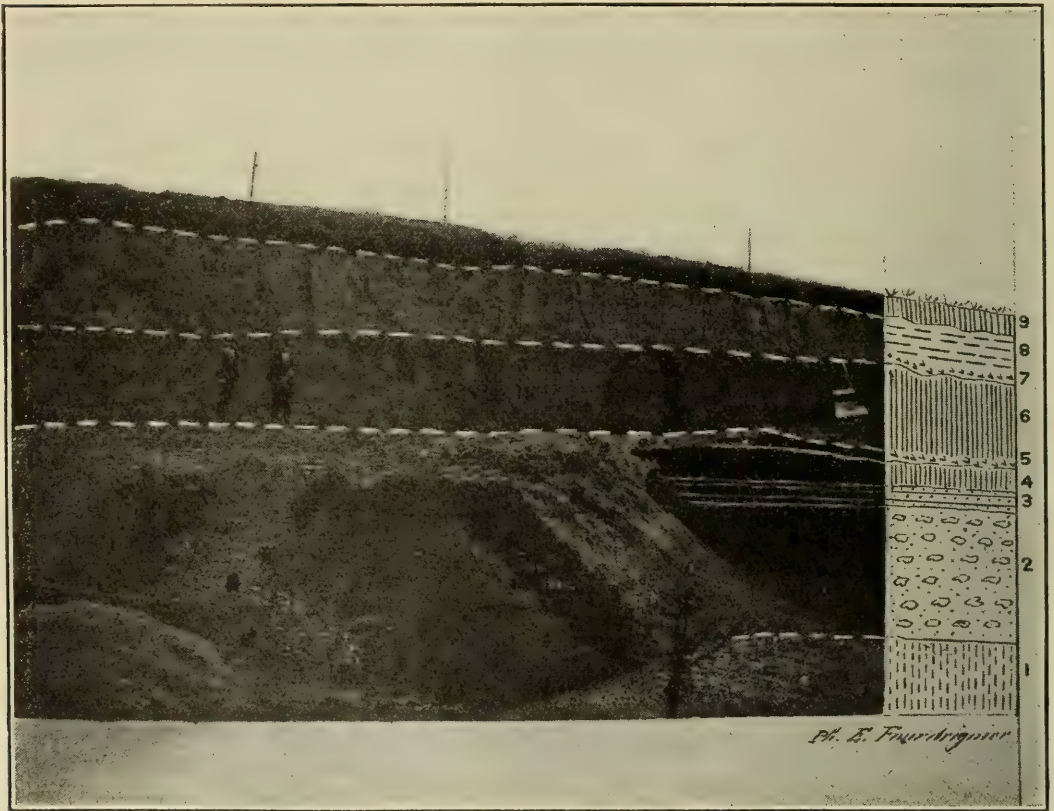


FIGURE 8.—Excavations on the "high Terrace" [II] at Saint Acheul

This is known as the *ancienne carrière Dupont* and more recently as the *carrière Bultel*, showing eight geologic layers, from the Upper Paleolithic deposits of brick-earth at the top (9) down to the sub-Chellean yellow gravels (2) overlying the chalk (1) at the bottom.

of the tufa there was discovered in 1893-1894 *early Acheulean* implements, somewhat more recent than the late Chellean *coups de poing* of Chelles.

The section of La Celle-sous-Moret (compare Osborn, 1915.2, pages 118, 166) is as follows:

Sheet of "lower loess" [corresponding with the arid period of late-cool-Acheulean].

Upper tufa levels, with flora of box (*Buxus*), fig-tree (*Ficus*), Canary laurel (*Laurus nobilis*), indicating a climate somewhat milder or more temperate than in the same region at the present time.

Middle tufa levels containing early Acheulean implements, discovered in 1893-1894.

Lower tufa levels containing sycamore-maple (*Acer pseudoplatanus*), willows, and pine, indicating a temperate climate. Pleistocene river gravels of 30-meter terrace.

Travertines, gypsum, and tufa (not tuff¹⁰), indicating a dry, semi-arid to arid climate, not necessarily volcanic disturbance.

Villefranche-sur-Saône, near Lyons.—This horizon, so much discussed and so badly interpreted by many prehistorians, seems to be at the bottom of a terrace of 30 meters. At one point it retains its normal altitude, at another point, where it has undergone secondary erosion, it actually rises only a few meters above the Somme River. A thick covering of loess rests on these fluviatile sands; what remains of the loess contains numerous flints belonging either to the pure late Acheulean or to the time of transition between the Acheulean and the Mousterian.

Acheulean Arrival in Belgium

Horizon of Sainte-Walburge in the Hesbayen loess.—The conclusions arrived at by the veteran archeologist, Marcel de Puydt, and his able colleagues, J. Hamal-Nandrin and Jean Servais (1912.1), are as follows:

"*Conclusions.*—La présence de silex taillés dans les alluvions de Liège nous amène aux conclusions suivantes:

"1° Le dépôt de la rue Jean de Wilde n'est pas éolien, du moins pour la partie qui renferme les silex taillés. 2° Le dépôt n'a pas été produit par une inondation. 3° Dans l'état actuel de nos connaissances, il ne peut avoir été constitué que par ruissellement. 4° Cette hypothèse du ruissellement rend compte des différences notables que présentent en Hesbaye deux coupes voisines. 5° L'homme et la faune quaternaire ont habité notre pays alors que les vallées principales étaient presque totalement creusées. Le relief du sol était donc alors sensiblement le même qu'aujourd'hui et n'a plus été modifié depuis que d'une manière insignifiante. 6° L'arrivée de l'homme quaternaire est postérieure à la formation des terrasses supérieures ou moyennes dans la

¹⁰ Tuff, to geologists, is a volcanic ash deposit which is observed about an explosive type of volcano following a violent eruption.

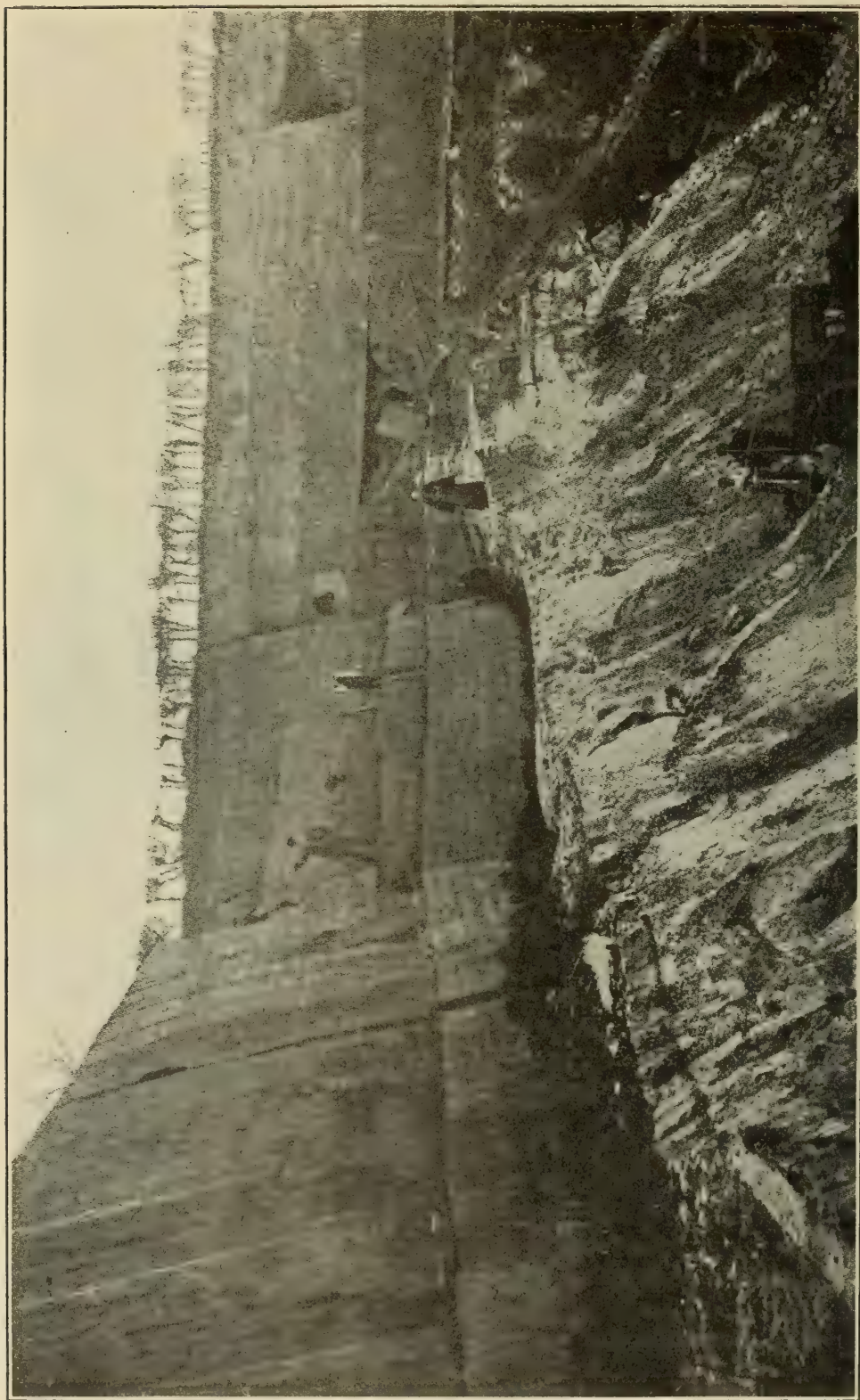


FIGURE 9.—*Liège Paleolithic, Belgium*

This view was taken November 14, 1911. At the base of the limon (Hesbayan loess) Marcel de Puydt is digging in the lower level. Near the middle of the limon J. Hamal-Nandrin points to the position of a pebble layer containing chipped flints. Referred to late *Acheulean* and early *Mousterian* times; close of Third Glaciation (III).

vallée de la Meuse et de ses affluents. 7° Si ces terrasses sont en relation avec des phénomènes glaciaires, ce qu'il faudrait encore démontrer, l'arrivée de l'homme acheuléen serait en tous cas postérieure à la formation des terrasses qui, aux environs de Liège, se maintiennent aux environs de la côte 70 au dessus du niveau des cours d'eau."

This locality is one of the most important in Europe, archeologically, as determined by Victor Commont of Amiens and Marcel de Puydt in 1911. The Hesbayan loess, horizon of Sainte-Walburge, a suburb of Liège, contains at its base an early Mousterian industry (*vieux Moustérien*) fashioned by a race contemporary with the mammoth and *Rhinoceros tichorhinus*. This Hesbayan loess (8 meters in thickness) is not regarded by the authors as of eolian origin, for it contains glacial boulders. The second hypothesis, that it is of fluvatile origin, also meets the grave objection that throughout the mass of loess are worked flints of Mousterian age. These authors believe they have demonstrated that previous to the early Mousterian—that is, the arrival of Mousterian man—the valleys of the Meuse and of its affluents eroded to their present actual level. The existing geographic relations had thus been established in preceding Acheulean times, as quoted in 7°, above cited. In the antecedent Acheulean industry, in caverns along the Meuse and its tributaries, we find Acheulean implements with the *Mousterian*, without any trace of deposition between them. Consequently, if we eliminate the eolian and fluvatile theories of deposition of the Hesbayan loess, only one interpretation remains, namely, that this loess is a stream deposit (*dépôt de ruissellement*). The geologic and archeologic succession is clearly shown in the accompanying sections, figures 9 and 10.

This loess was redeposited after the alluvial depositions of the "high" and of the "middle" terraces. Theoretically, the true Hesbayan loess corresponds to the ancient loess of other localities. Consequently the industry of its base is of Acheulean age, but throughout the middle and upper layers is found an archaic Mousterian. The formation is that of tributary streams pouring out of ravines and redepositing the loess on the Hesbayan plateau. Here were united the three conditions necessary for the existence of the tribes of the Stone Age, namely: (1) Immediate proximity of water; (2) proximity of flint material ready for the industry; (3) presence of extensive hunting territory.

The authors emphasize the fact that from the beginning of Prepaleolithic time, the valleys being completely eroded, we should not expect to find ancient camps high above the level of the streams.

Terrace levels of Belgium.—The authors again emphasize the terrace levels, which concur with those observed in France by Depéret:

"On voudra bien se rappeler que prenant pour zéro la cote moyenne du niveau d'eau dans une vallée de Belgique, on trouve, en partant du bas: une *basse terrasse* s'élevant de 5 à 10 m. au-dessus du niveau de l'eau, une pente rapide, une *moyenne terrasse*, s'élevant de 30 à 65 m., une nouvelle partie rapide, une *haute terrasse*, s'élevant de 100 à 130 m., environ. Ce n'est qu'au-dessus de 130 à 140 m. que commence le *haut plateau*. A Sainte-Walburge on se trouve donc précisément à la limite de la haute terrasse et du haut plateau."

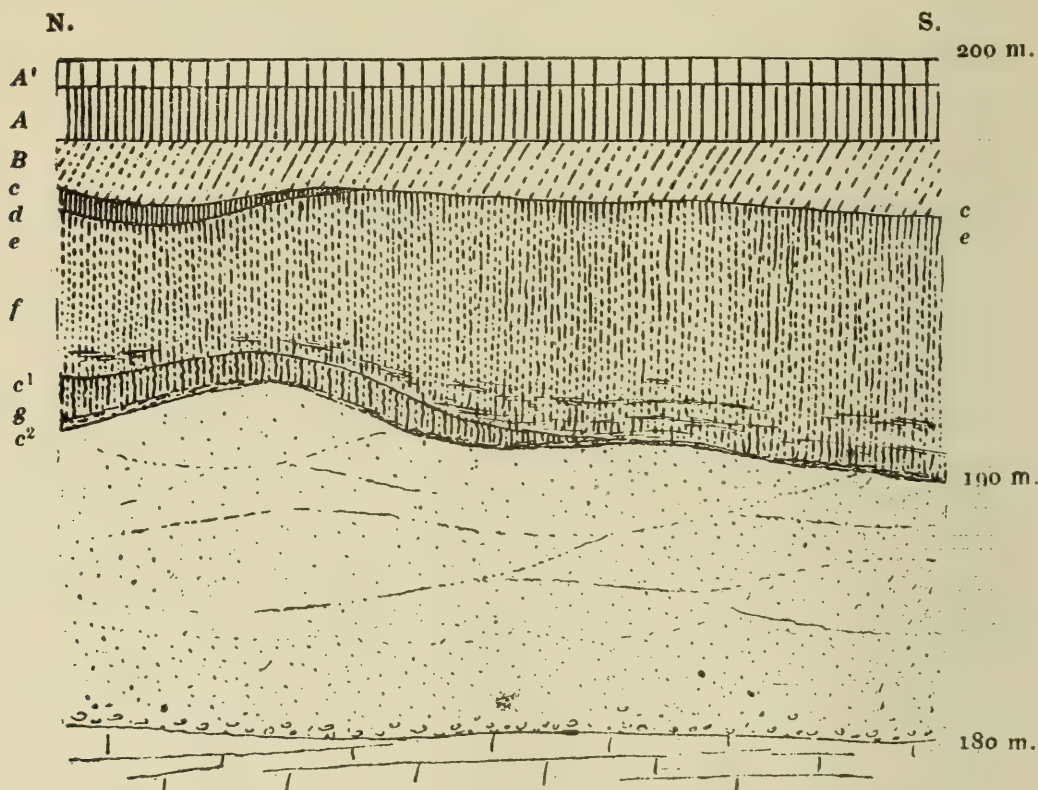


FIGURE 10.—Section of the Hesbayen Loess, Saint Walburge, Belgium

After De Puydt, Hamal-Nandrin, and Servais, 1913.

- A'—Humus and redeposited loess.
- A—Brick earths.
- B—Pale yellow loess of eolian origin.
- c—Rare flints of Mousterian age.
- d—Mousterian flints.
- e, f—Ancient Mousterian flints and traces of superior Acheulean.
- c¹—Pebbled layer.
- g—Argillaceous layer in red loess.
- c²—Pebbled layer.

Obermaier characterizes the section as follows: "Ce que nous voyons ici comme stratigraphie est au fond très simple. Il y a, en haut, de la terre à briques; ensuite un limon doux qui correspond très probablement au löss récent et doit être, pour moi, de formation plutôt éolienne. En bas, une couche d'environ cinq à six mètres de limon. Ce dernier limon n'est pas, pour moi, un niveau déterminé, mais bien une formation due au ruissellement, formation à laquelle, certainement, est venue se mêler une certaine quantité de löss ancien de formation éolienne."

Both as to the relation of the industry to the terraces and as to the mode of deposition of the loess, the authors differ widely from the theory held by A. Rutot, the distinguished archeologist.

Correlation: Mousterian Industry = Beginning at the End of Arid Lower Loess and extending through IV Glacial Maximum (Würm of Penck, Monastirian of Depéret) = Terraces of 18-20 Meters

This correlation is the most firmly established of any. The transition between the Acheulean and Mousterian industries, known as Acheuleo-Mousterian, is gradual and archeologists differ in the application of terms. Schmidt, for example, regards Krapina, with its Neanderthaloid men, as a true Acheulean station of the same age as the "loess" station of Ehringsdorf, but lacking some of the typical implements, while the discoverer of Krapina man, Gorjanovič-Kramberger, also Breuil and Déchelette, regard the Krapina implements as of the so-called warm Mousterian, inasmuch as the last elements of the warm fauna survived, namely, Merck's rhinoceros and the straight-tusked elephant (*E. antiquus*). The industrial and climatic divisions of the Mousterian (compare Osborn, 1915.2) are as follows:

<i>Late Mousterian industry of La Quina.</i>—Life and industry of the Neanderthal races, chiefly in the shelters, grottoes, and entrances to the caverns.	Spread of all the arctic and tundra mammals over western Europe, including the musk-ox; southern migrations of lemmings of the steppes.
--	--

<i>Middle or Full Mousterian industry of the Neanderthal race.</i>—Life and industry chiefly in the shelters, grottoes, and entrances to the caverns.	Appearance of arctic and tundra life, mammoths and reindeer, including mammals and birds of the Arctic region, first forerunners of the northern steppe life.
--	--

<i>Transition from the Mousterian to the late Acheulean industry, the so-called Acheuleo-Mousterian.</i>—Stations of La Micoque and Combe-Capelle. Tribal life. Industry partly in open stations, partly under sheltering cliffs.	So-called "warm Mousterian" fauna, including probable northward migrations during the summer season of the hippopotamus, Merck's rhinoceros, the straight-tusked elephant, animals observed in association with the Mousterian culture as far north as the Somme Valley at Montières-lès-Amiens and along the Vézère Valley, Dordogne.
--	---

In the temperate climate of northern Italy the men of early Mousterian times were contemporaneous with the hippopotamus, the straight-

tusked elephant, and Merck's rhinoceros. There is evidence that Merck's rhinoceros and the straight-tusked elephant lingered in southern and western Europe during the whole period of the early development of the Mousterian industry. On this point Mayet (1921.2, page 486) observes:

"Le Moustérien se place en partie dans l'interglaciation Riss-Würm. On objectera qu'alors le Moustérien à faune froide se trouve commencer dans une période interglaciaire. Mais, dans divers gisements, à Villefranche notamment—le Moustérien ancien se rencontre associé à une faune chaude à *Rhinoceros Mercki* et si une période interglaciaire suppose un réchauffement climatérique dans sa première partie (fonte et retrait des glaces, phase de creusement rapide des vallées . . .) une nouvelle extension glaciaire est, nécessairement, la conséquence d'une phase froide et surtout humide pendant la moitié ou les deux tiers terminaux de la période interglaciaire—et cela répond bien à ce que l'on peut constater pendant la longue évolution des industries et de la faune moustériennes."

The terrace of 18–20 meters.—The horizons included in the terrace of 18–20 meters and exhibiting the Mousterian industry associated with a cold tundra fauna, the mammoth (*Elephas primigenius*), the woolly rhinoceros (*Rhinoceros tichorhinus*), reindeer, etcetera, are numerous and their stratigraphic localization in these deposits calls for no further discussion; for example, at—

(1) Saint Acheul and Montières, in the valley of the Somme, as observed by Commont (Commont, 1914.1);

(2) Lower terraces of the valley of the Seine, near Paris, as observed by Chaput (Chaput, 1921.1);

(3) Levallois, Grenelle, Bois-Colombe, etcetera, in the valley of the Seine;

(4) Artins, La Jarretière, in the valley of the Loire (Chaput, 1917.1);

(5) Pierrefitte-sur-Loire, in the valley of the Loire, below Digoin (Chaput, 1917.1).

The Mousterian industry (*pointes, racloirs, lames*) is everywhere found associated with a cold fauna in the terrace of 18–20 meters, or *Monastirian*. This relation, constantly observed in all valleys, is admitted by all archeologists. It is nevertheless true that in the *south of Europe* the warm fauna (*Moustérien chaud*, "warm Mousterian") persists at the base of 20 meters (Summary by Depéret, 1921.1, page 126). Commont believed that he found a "warm Mousterian" fauna in the Somme gravels, but Vayson (1920.1, page 449) discredits it.

*Correlation: Aurignacian Industry = Recession of Glaciation IV (Würm)
continued into beginning of Postglacial Time = End of
Monastirian Stage of Depéret = Ter-
races of 18-20 Meters*

The Aurignacian industry corresponds with the end of the Monastirian Stage of Depéret (Mayet, 1921.1, page 6). The researches of Mayet and Pissot (1915.1) establish the inclusion of an Aurignacian industry in its final stage near the summit of the 20-meter terrace in the valley of the Ain in the rock shelter of La Colombière. The Aurignacian begins with the advent of a new race of men in Europe, the Cro-Magnon, to replace the Neanderthal workers of the Mousterian industry. Subsequent to this filling in of the 20-meter terrace in the valley of the Ain we find superficial layers containing the more recent industries of Solutrean and Magdalenian time. Mayet has demonstrated (Depéret, 1921.1, page 127) that the final Aurignacian industry, with its cold associated fauna, is intercalated in the shelter of La Colombière (Ain) at the very summit of the 20-meter terrace. The cultural and climatic divisions of the Aurignacian are as follows:

Late Aurignacian.—Late Aurignacian and Solutrean flint workers seeking many open stations. The two industries partly contemporaneous, the Aurignacian pursued by the Cro-Magnon artistic race, the Solutrean at the same time by an invading race from the east, possibly the Brünn. Departure from Mousterian fashion of chipping the flakes; Aurignacian "retouch" weakened; increase of fine flint tools for art work; primitive shouldered spear-head (*pointe à cran*) at Willendorf, Austria, and in the Grimaldi caves on the Riviera, associated with prototypes of Solutrean culture; carving on reindeer horn.

Middle Aurignacian.—Perfection of the flake industry and culmination of the Aurignacian "retouch"; increase in number and variety of graving-tool flints in the Pyrenees and in the Dordogne region; also at La Trilobite, on the headwaters of the Seine.

Grotto life near headwaters of the Danube, associated with the "lower rodent layer," the Obi lemming, woolly rhinoceros, woolly mammoth, stag, and reindeer. Arid "newer loess" fauna of Achenheim, near Strasburg, of Völklinshofen; also down the Danube to Willendorf, Austria, and Brünn, Moravia, center of Solutrean industry. Appearance of Asiatic steppe forms, of the kiang, and of the Saiga antelope.

Final northward retreat and disappearance of the northern types of lemming, the banded (*Myodes torquatus*) and the Obi (*M. obensis*), and other small tundra forms.

Early Aurignacian.—In Tunis, in Typical tundra fauna, woolly mammoth and reindeer of cold-moist early Dordogne (Abri Audit, Châtelperron), and in the Pyrenees, related to Postglacial times. No evidence of preceding Mousterian industry, in aridity. part due to Neanderthal influence, in part to Cro-Magnon invasion.

The following geologic, archeologic, and paleontologic correlations of the Pleistocene have been summarized in the table after Depéret and Mayet.

Depéret concludes: The arrival of Chellean man does not correspond to lower Quaternary time, but dates solely from the Tyrrhenian Epoch of the terrace of 30 meters. In the preceding epochs of Sicilian terraces (90–100 meters) and of Milazzian terraces (55–60 meters) no industrial or other evidence of the existence of man in Europe has thus far been found, leaving aside the question of eoliths. The *Chellean* industry corresponds with the base of the 30-meter terrace. The *Acheulean* industry occurs higher up on the 30-meter terrace. The *Mousterian* industry occurs on the 18–20-meter terrace. The *Aurignacian* industry occurs in the upper part of the 18–20-meter terrace. In the final *Magdalenian* industry the valleys were nearly down to their actual present level.

TABLE IX

GEOLOGIC, ARCHEOLOGIC, AND PALEONTOLOGIC CORRELATION OF THE PLEISTOCENE

Depéret, 1918-1921; Mayet, 1920-1921

Fauna.	Recent.	Flint industries.
	Fourth Postglacial moraines.	Azilian, Tardenoisian, Magdalenian, Solutrean.
QUATERNARY = PLEISTOCENE = AGE OF MAN.	IV. <i>Monastirian Stage</i> , Depéret.—After Monastir, Tunis. Mediterranean shoreline of 18-20 meters. Lower river terraces of 18-20 meters. Glacial moraines of IV GLACIATION = Alpine-Würm of Penck (Würmien-Mecklenburgien). <i>Mousterian</i> industry in formation. Cold mammoth-reindeer fauna.	Aurignacian.
	Third Interglacial regressive period = Riss-Würm recession of Penck.	(Cold.) Acheulean.
	III. <i>Tyrrhenian Stage</i> .—Defined by Issel, horizon of <i>Strombus bubonius</i> . Mediterranean shoreline of 28-32 meters. Erosion of middle river terraces of 28-32 meters. Glacial moraines of III GLACIATION = Riss of Penck (Rissien-Polonien). <i>Chellean</i> industry at base of 30-meter terrace. Primitive amygdaloid weapons and warm hippopotamus fauna associated.	(Warm.) Chellean.
	Second Interglacial regressive period = Mindel-Riss of Penck.	(Pre-Chellean?)
	II. <i>Milazzian Stage</i> Depéret.—After peninsula of Milazzo, northern Sicily. Mediterranean shoreline of 55-60 meters. Middle-high river terraces of 55-60 meters. Glacial moraines of II GLACIATION = Mindel of Penck (Mindélien-Saxonien). Maximum glacial extension in northern and southern Europe. First Interglacial regressive period = Günz-Mindel of Penck.	"No traces of the existence of man on continent of Europe." Mayet, 1921.
	I. <i>Sicilian Stage</i> (=Cromerian, England).—Gulf of Conque d'Or, Palermo, Sicily. Mediterranean shoreline of 90-100 meters. Erosion of highest river terraces of 100 110 meters. Glacial moraines of I GLACIATION = Günz of Penck (Günzien-Scanien).	

Correlation: Solutrean Industry contemporaneous with late Aurignacian and early Magdalenian Industries = Second Arid or "Middle Loess" Period = Achenschwankung of Bühl and Penck

As Mayet observed (1921.2, page 487), the Solutrean is, in a sense, a

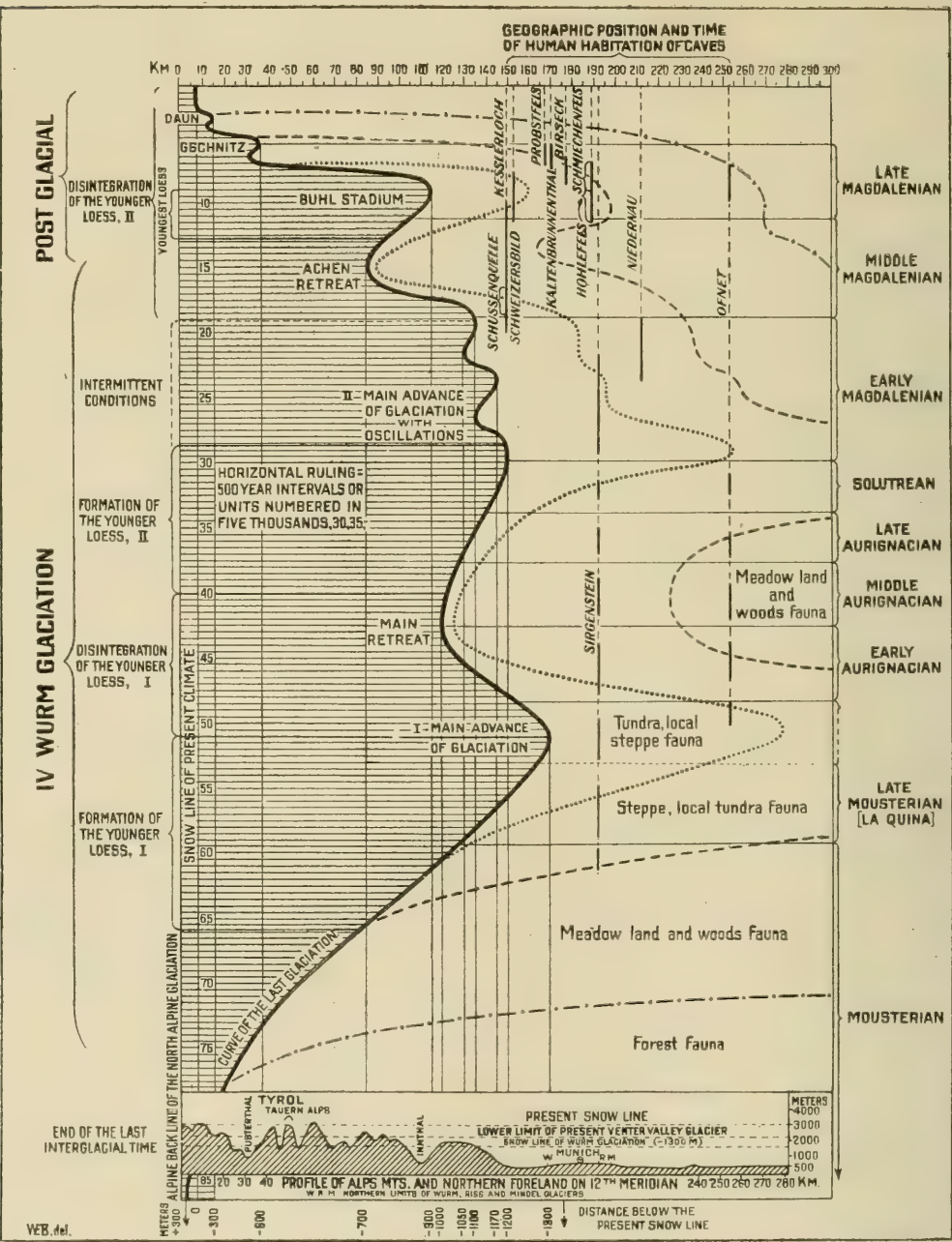


FIGURE 11.—Graphic Presentation of the last Alpine [Würm] Glaciation
After Soergel, modified by Chester A. Reeds.

collateral industry, which evolved in eastern Europe contemporaneously with the last phase of the Aurignacian industry and the early phase of

the Magdalenian of the west. At some stations the industry is intercalated between the late Aurignacian and the early Magdalenian. At other stations, where the Solutrean flint workers did not extend their influence, the late Aurignacian is directly superposed by the early Magdalenian through gradual evolution of industrial forms. Many authors are agreed that the Solutrean industry was contemporaneous with the first Postglacial recession, or *Achenschwankung*, of the Alpine glaciers, during which a dry and very cold climate prevailed, with dust-storms and widespread deposition of "middle loess" over western Europe; flint workers seeking many open stations, horses and wild asses numerous on the prairies. Soergel, of the University of Tübingen (1919.1), however, correlates the Solutrean with the maximum stand of the second advance of the Fourth Glaciation (figure 11, Soergel and Reeds).

The correlation of human industries with the glacial and climatic phases succeeding the second maximum of the Fourth Glaciation has been admirably summarized by Soergel in his work cited and emended by Mayet and by Gignoux, who have cooperated with Depéret in the new correlation of the Quaternary. Finally, in the Magdalenian Epoch (Depéret, 1921, p. 127), the valleys were eroded down nearly to their actual present level.

Soergel (1919.1, page 78) presents also a generalized normal climatic curve of glacial and interglacial times (figure 12).

3. CORRELATION OF THE DE GEER GEOCHRONOLOGY WITH HUMAN INDUSTRIES

According to the Swedish archeologist Montelius (1920.1), the Aurignacian period of human industries is supposed to have begun about 20,000 years ago, when the Fourth Glaciation occupied north Germany and Denmark. It probably lasted nearly 5,000 years. The Solutrean period began about 15,000 years ago, when the southern coast of Scania became ice-free. As the ice melted in Scania, plants and animals immigrated there, and with them came man. The oldest implements that we can expect to find on the southern and western coasts of Sweden and Norway, as souvenirs of man, ought to be such as are contemporary with implements of the Solutrean period found in central Europe. They are exactly of the same type. (2) The next period, the Magdalenian, is characterized in Sweden by the preponderance of bone weapons and small flint flakes, as in central Europe. Many of these objects have been preserved in peat bogs. (3) In the next period, the Azilian, the characteristic types occur in both regions. (4) In the following Campignian period characteristic flints occur in both areas. In the north they are

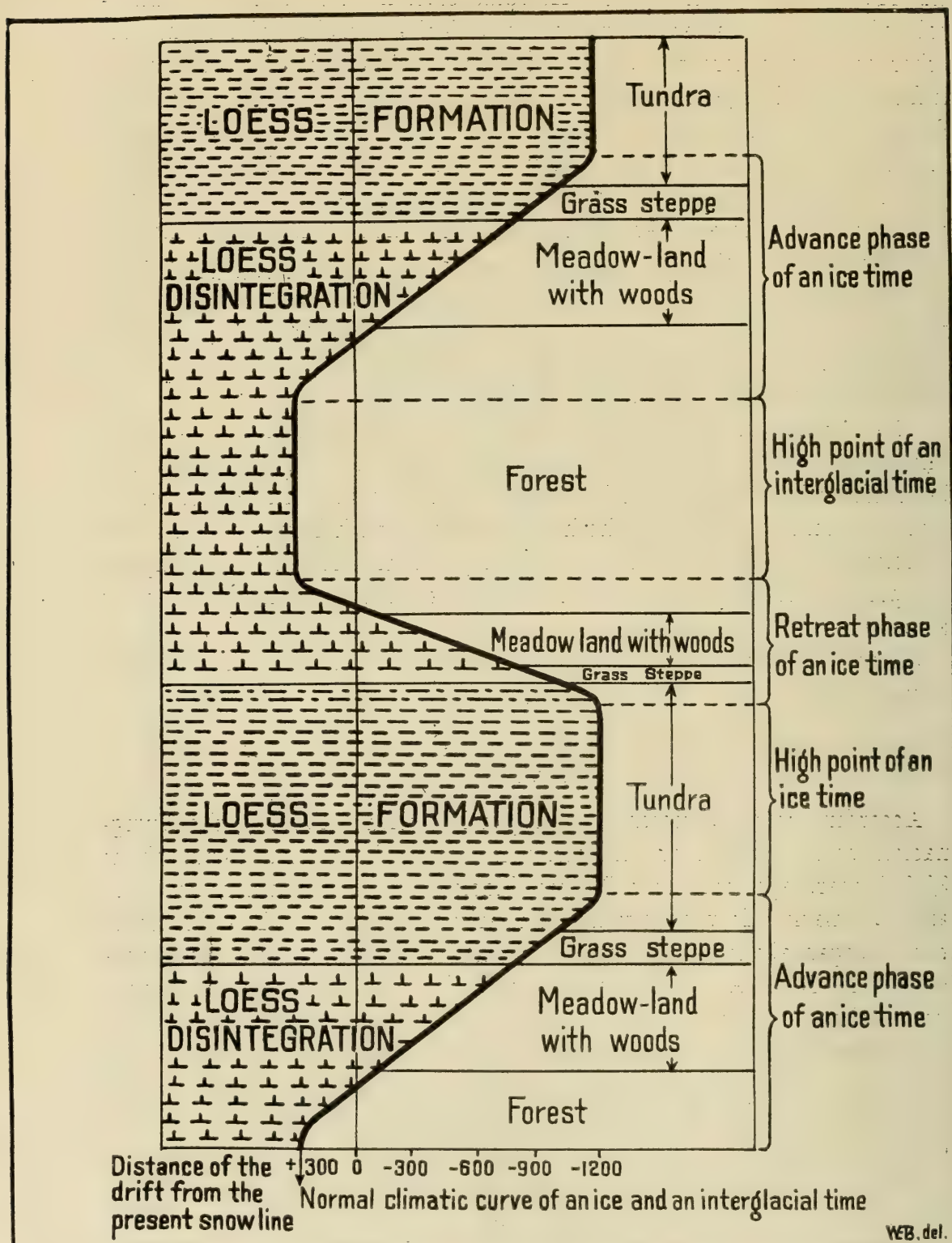


FIGURE 12.—Normal climatic Curve of Glacial and Interglacial Times

After Soergel, modified by Chester A. Reeds.

common in the shell-mound period, which represents the transition from the Paleolithic to the Neolithic. (5) The first race of men that came to Sweden, hunting the reindeer and other animals following the retiring ice border, must have been the dolichocephalic Cro-Magnon race of central Europe. No new immigrations of other races seem to have occurred, and the conclusion is reached, and supported by many facts, that the Cro-Magnon man is the ancestor of the present-day Swedes.

The important events in the chronology of Scandinavian cultures appear in the following table:

CHRONOLOGY OF SCANDINAVIAN CULTURES

Approximate chronology of the Paleolithic, Neolithic, Copper, and Bronze cultures of western Asia and Europe. These dates are largely conjectural and may be greatly modified by future discoveries.		Archeologic chronology of southern Scandinavia as given to the author by Oscar Montelius in the summer of 1921, slightly modified by the more recent determinations of De Geer and Antevs that the ice retreated from central Scania not earlier than 11,500 B. C.	
AGE OF BRONZE in central Europe, France, Spain.....	}	B. C.	AGE OF BRONZE.
HORSE domesticated in the Orient	}	2000	
		2200-1700	{ STONE CISTS. Inferior pottery. First appearance of BRONZE in Sweden.
COPPER used in central Europe and France.....	}	2500	PASSAGE GRAVES. Painted pottery. First appearance of COPPER.
AGE OF BRONZE in Troy, Greece, and Sicily.			
AGE OF BRONZE in Egypt and Chaldea	}	3000	Earliest Scandinavian SKULL of NORDIC type. DOLMENS—round or rectangular.
COPPER used in Troy, Greece, Sicily, Hungary, and Spain..			
COPPER used at Anau, Turkestan	}	4000	{ Dawn of the NEOLITHIC, no Megalithic tombs, stone axes developed from <i>pic</i> .
COPPER used in Egypt and Chaldea			
		5000	SHELL MOUND and CAMPIGNIAN cultures. STAG PERIOD.
		6000	

	7000	{	MAGLEMOSE (Mullerup) cul- ture of Denmark—DOMES- TIC DOG.
CAMPIGNIAN culture in France.	8000	{	MOOSE (ELK) PERIOD in Scania.
NEOLITHIC culture at Anau, Turkestan			
	9000		
	10,000	{	OUR ANCESTORS ARRIVE IN SCANDINAVIA with large flint implements and axes of reindeer horn.
Close of REINDEER PERIOD in Southern France	11,000	{	REINDEER PERIOD in Scania.
	11,500	{	Final retreat of the Scandi- navian Glacier from south- ern Scania.
Crete settled.....	12,000		
	13,000		
	14,000		
	15,000		
MAGDALENIAN (Paleolithic) cul- ture in France.....	16,000	{	
NEOLITHIC culture at Susa, Persia			
	17,000		
Beginning of NEOLITHIC in southwestern Asia	18,000	{	

4. THEORETIC CORRELATION OF QUATERNARY GEOLOGY, ARCHEOLOGY, AND
MAMMALIAN PALEONTOLOGY, ACCORDING TO OUR KNOWLEDGE OF 1921

BY OSBORN AND REEDS

The diagram, figure 13, is a summary of Section I and Section II of the present contribution, in which, according to our *actual knowledge*, the (1) stages of human life, of (2) human races, of (3) archeology, are correlated with (4) theoretic succession of plant life, (5) the more or less theoretic glacial and interglacial stages, (6) the actual river terraces, and (7) the changes in sealevel.

In the center of the diagram the vertical dotted line represents the modified Penck-Brückner estimates of the advances and retreats of the four glaciations in the Alpine region, with intervals between them expressing the relative duration of the three interglacial periods.

To the left of the center is the theoretic correlation of these Glacial I-IV and Interglacial 1-3 epochs in the whole Northern Hemisphere, the Holarctic region of the zoologists.

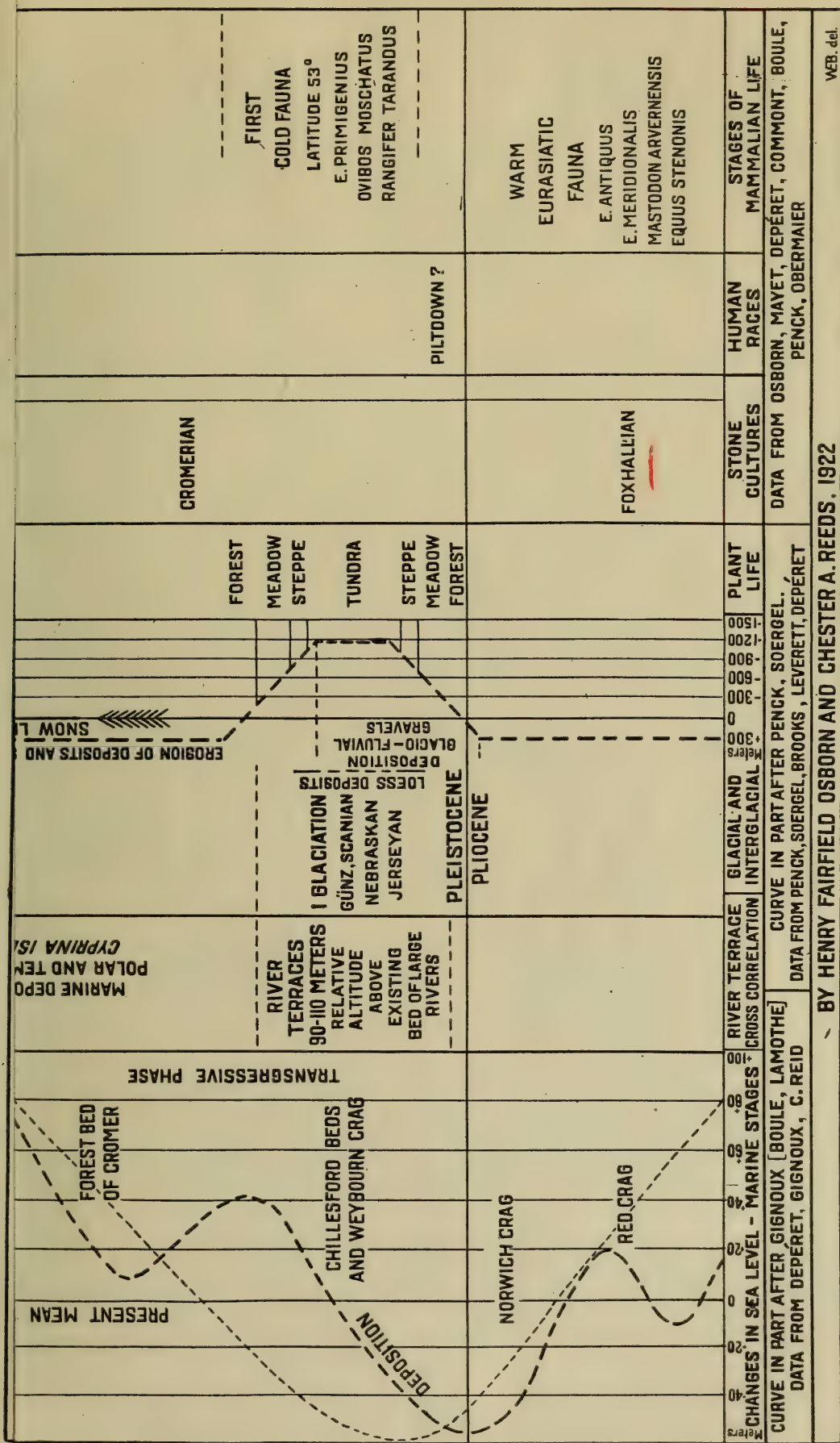


FIGURE 13.—Correlation of marine, terrace, climatic, racial, culture, and life stages of the Pleistocene and Upper Pliocene Periods

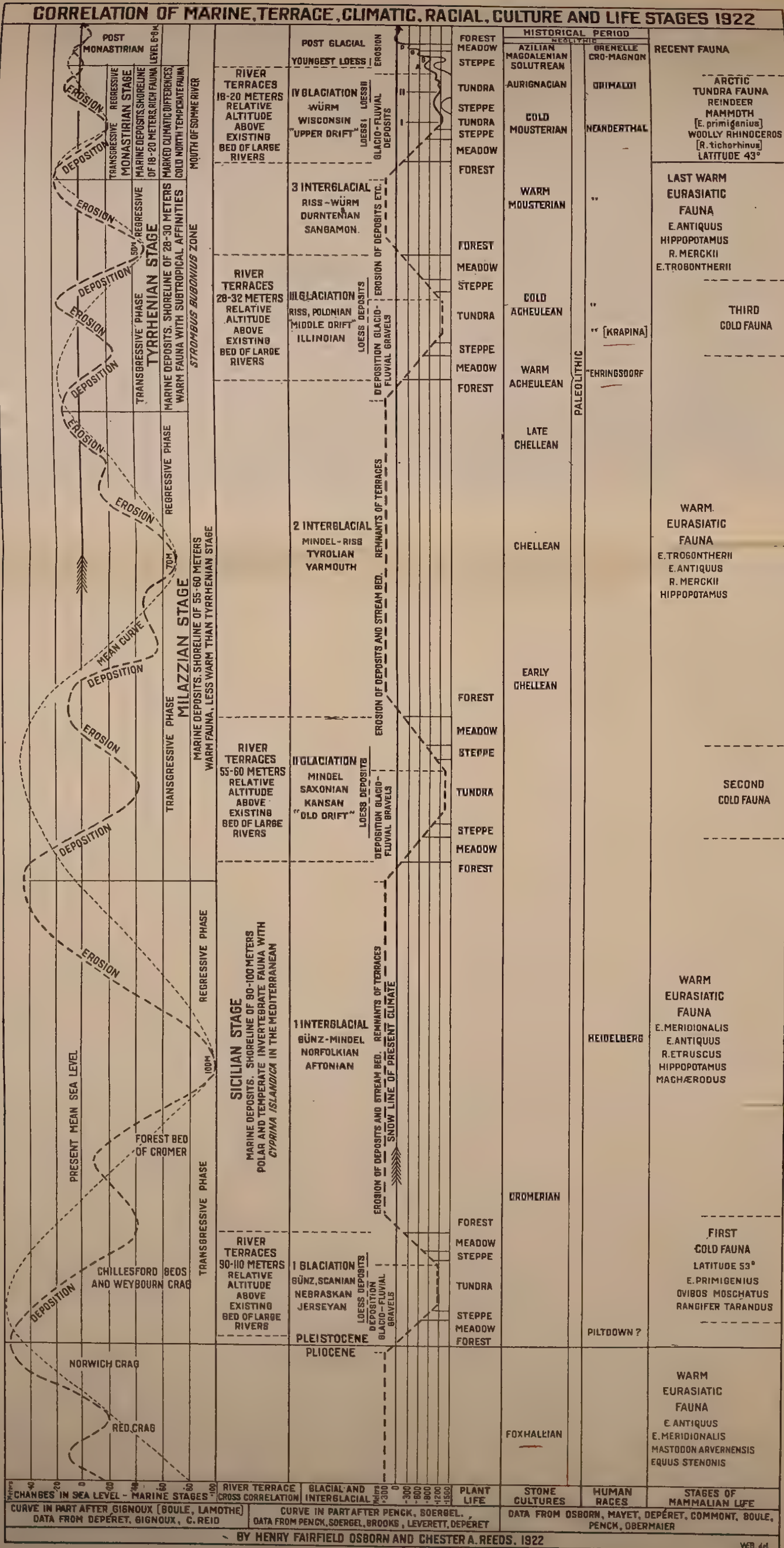


FIGURE 13.—Correlation of marine, terrace, climatic, racial, culture, and life stages of the Pleistocene and Upper Pliocene Periods

Also to the left is the river terrace column, which furnishes the meeting ground, or *liaison*, between the Penck-Brückner system of glacial stages and the Depéret system of marine stages.

It will be observed that the SICILIAN stage of Depéret corresponds broadly with GLACIATION I and *Interglaciation* 1 of Penck and Brückner; that the MILAZZIAN stage of Depéret corresponds broadly with GLACIATION II and *Interglaciation* 2 of Penck and Brückner; that the TYRRHENIAN stage of Depéret corresponds broadly with GLACIATION III and *Interglaciation* 3 of Penck and Brückner; that the MONASTIRIAN stage of Depéret corresponds broadly with GLACIATION IV of Penck and Brückner.

Thus the divisions of the Quaternary contained in the Depéret system are practically coincident with the divisions of the Quaternary contained in the Penck-Brückner system. This coincidence is very significant. It shows that, according to both systems, glacial advances correspond with periods of regression of the sea, elevation of the land, and erosion; that interglacial epochs correspond with periods of transgression of the sea, depression of the land, and deposition. This concordance of the Penck-Brückner system and the Depéret system is very important if it can be firmly established by further observations.

It leaves for future observation the primary causes of *marine transgression* and *regression*. As pointed out in Section III (Appendix) of the present contributions, Depéret holds to the *eustatic theory*; he believes the primary cause of marine transgression is the actual elevation of sealevel. This opinion is supported by many geologists and physiographers. On the other hand the geologists and physiographers hereinafter quoted in the Appendix maintain that the sealevel remained substantially the same throughout Quaternary time; that the primary cause of marine transgression is continental depression.

Aside from these debatable aspects of the bases of Quaternary time divisions, figure 13 marks a profound change in the opinion of the joint authors since 1914, when the first Osborn-Reeds correlation table of this kind was published in "Men of the Old Stone Age." The senior author now assigns a much greater antiquity to the Piltdown and Heidelberg stages in the evolution of man and to the early Chellean stage in the evolution of human culture. The grounds for this are fully stated in the pages and tables of the present Section II of this contribution. The recent discovery of the Foxhallian industry of the Red Crag and of a still more ancient pre-Red Crag industry profoundly modifies our former relatively conservative views, both as to the antiquity of man and the

antiquity of the genuine flint industry. Man is not only far older than we formerly supposed, but human industry is far more ancient.

III. APPENDIX: REVIEW AND CRITIQUE OF THE PENCK-BRÜCKNER, DE GEER, DEPÉRET SYSTEMS, FROM NOTES BY LEVERETT, ALDEN,
DE MARTONNE, JOHNSON, AND DAVIS

COMMENTATORS ON THE PAPER

The full manuscript of the present communication to the Geological Society of America was submitted to Frank Leverett, of the United States Geological Survey, before its presentation to the Society. Some of Mr. Leverett's comments and corrections have been inserted in the text; other comments are included in this *Appendix*. At the time the paper was presented to the Society it was informally discussed by Prof. W. M. Davis, Mr. Frank Leverett, and Dr. Ernst Antevs. An abstract was subsequently given before the New York Academy of Science on January 16, 1922, and valuable comments were made by Prof. Douglas Johnson, geographer of Columbia University, who has also been in correspondence with Prof. Emmanuel de Martonne, of the Sorbonne, on the subject.

It seems very important, in the interest of clarity of thought, to distinguish between Quaternary phenomena which are regarded by all as practically determined and phenomena which are still *sub judice*.

VIEWS OF FRANK LEVERETT, OF THE U. S. GEOLOGICAL SURVEY

(1) Leverett considers that Depéret has made the case entirely too simple, and that future detailed study will bring out complications which he has not taken into account. It appears doubtful if the uplifts have really been as *uniform* as Depéret states; for example, for oldest Quaternary 95–100 meters; for the next stage, 55–60 meters, etcetera. In North America the uplift has been *differential*, so that one part of the coast has suffered an uplift of 100 meters while a neighboring part has had no uplift, and the intervening territory passes from 0 up to 100 meters. It would take a lifetime of field-work in this country for a geologist to run out the relations of the river terraces to the several stages of glaciation, and only a small part of such correlation has yet been done. So it would be impossible in North America to make any such broad and full correlations as Depéret has done in the European field.

(2) Leverett considers that there is a fundamental error involved in Depéret's new method of correlating fluvial plains, that head in the

glacial drift, with the marine shorelines of the sea into which the streams from these plains discharged. Depéret first conceived this method while studying the features around Lyons. He there found, as indicated in his paper of May 5, 1919 (1919.1), that the outer moraine connects with a terrace 55 to 60 meters above the Rhone, while other moraines, which he designated "Neorissian," connect with a terrace 30 meters above the stream. This eventually led Depéret to conclude that the outer moraine is of Mindel age and not a Riss moraine, as classed by Penck, and that his Neoriss is the true Riss moraine.

(2a) In opposition to Depéret's view, Leverett points out that the outer moraine in that part of France is well enough preserved to be classed as Riss moraine, and he regards Penck, instead of Depéret, as correct. Penck, no doubt, was familiar with all the differences in the heights of terraces connecting with the several moraines, and knew that the inner ones were tied to a terrace 30 meters above the stream, and the outer ones to a terrace 55-60 meters, and probably was able to explain the reason for this difference when the difference in age is not very great. Leverett has observed several cases of this sort, where inner moraines of the last, or Wisconsin, stage of glaciation connect with a much lower river terrace than do the outer moraines. This is notably true on the Illinois River, where the outer moraine has connection with a terrace 170 feet above the river, while moraines farther up, near Hennepin, connect with a terrace 50 feet lower. At the time these moraines were formed the glacial drainage had cut down the part of the valley near the outer moraine more than 50 feet, so there was a fall from Hennepin down the valley through the outer moraine. In this case the material was sandy gravel, which the glacial stream could easily remove. This may also be the explanation in the case of the Rhone Valley terraces.

(2b) More in detail, Leverett considers that the correlating of these terraces on the Rhone near Lyons with marine shorelines that stand precisely the same height above the sea as these terraces do above the Rhone is a matter that would involve considerable field-work along the entire interval from Lyons to the mouth of the stream. He is therefore inclined to think that the lowering in the vicinity of Lyons, from the 55-60-meter terrace down to that of 30 meters, is referable to a cutting away of some sand and gravel deposits below Lyons, rather than to any effect which the lowering of the Mediterranean might have had. This much is certain: that the Rhone Valley was greatly filled by glacial deposits, so it would not be surprising if some glacial deposit acted as a barrier to hold the stream up to 55-60 meters. It may, therefore, have taken but

a slight amount of stream-work to remove this barrier and lower it to the 30-meter terrace.

(3) An important feature of Depéret's theory is that he attributes the *elevation* and *depression* of the shorelines chiefly to *upward or downward movements of the sea* (eustatic theory), as distinguished from *upward or downward movements of the land* (epirogenic theory). Leverett remarks, therefore, that it may be profitable to attempt to set forth the amount of variation in level (that is, eustatic) which the sea is likely to have had, and thus determine whether it is necessary to call in any uplifts and subsidences of the land (that is, diastrophic). The fluctuations of the sea seem to depend entirely upon the amount abstracted in forming ice-sheets, and in returning the water again, by the melting of the ice. On this subject Penck has written several papers, but probably the best discussion is that by Daly in his paper, "The Glacial-control theory of coral reefs" (1915.1). On page 173 it is pointed out that an average *lowering* of the sea of 25 fathoms (46 meters) is likely to have occurred in all the stages of glaciation. This he later raised a little, making it 50–60 meters, or a maximum of about 200 feet. If the earth should become ice-free the sea level would probably be raised somewhere between 11 and 37 meters *above* the present sea level. This wide range is due to our lack of knowledge of the amount of ice in the existing ice-sheets. There may then, in *preglacial* time, have been a sealevel from 11 to 37 meters *higher* than the present sealevel. In the glacial stages the sea may have been 50 meters or 60 meters *lower* than the present. In the interglacial stages the sealevel is likely to have been *about the same* as at present, unless the Antarctic and Greenland ice-sheets were completely melted, in which case it would have stood 11–37 meters higher than at present.

(4) According to Leverett, it follows that if there were no diastrophic movements, the shorelines of the several glacial stages would have been so far below the present sealevel that they would have no exposure in the region discussed by Depéret. So that any reference he makes to shorelines of glacial age that are visible *must involve the work of diastrophism* to bring them to view. It appears to Leverett that Depéret is radically wrong in trying to rule out diastrophism, and at the same time to have the glacial shorelines high enough to be visible above the present sealevel. It is, perhaps, of still more importance to note that if there had been no diastrophism the sea could not have reached a level more than 11 to 37 meters above the present, and that, too, in an ice-free condition of the earth. The Quaternary marine shorelines at 100 meters and 55–60 meters are thus entirely too high to be in accord with an

hypothesis that excludes diastrophism. It would seem that it must be apparent to any one at all familiar with the subject that it is necessary to bring in diastrophism to account for the fluctuations of the sealevel.

(5) Leverett considers that the correlation both of the Tyrrhenian and Sicilian stages of Depéret is too loose. For example, Depéret includes within the Tyrrhenian the temperate fauna of an interglacial stage which precedes the Polonian-Rissian glaciation; he allows a stage of glaciation also to fall within the Tyrrhenian; furthermore, he refers the cold Postglacial fauna to a terminal phase of the Tyrrhenian. He thus takes no account of a possible lowering of the sealevel (eustatic movement) in the glacial stage by the abstraction of water to form the ice-sheet, but from the presence of a 33-meter beach *on top* of the glacial deposits, as well as of a beach of 33 meters *beneath* the glacial deposits, he takes the altitude of 33 meters as a basis for correlating both interglacial and glacial stages with a stage of the Mediterranean Sea of 33 meters.

(5a) Similar laxity is shown in Depéret's attempt to *carry the Sicilian correlation* of 90–100 meters into the glaciated districts around the Baltic and North seas. The Sicilian is thus made to correlate with the Scanian; also with an interglacial stage between the Scanian and the Saxonian. Against this correlation is the fact that the sea was actually low in the Baltic basin in the interglacial stage between the Scanian and the Saxonian. [The sea was low for only a portion of the stage; see final correlation chart by Osborn and Reeds, figure 13.] The interglacial *Paludina* fresh-water beds at Berlin lie 40 meters below the present streamlevel. These *Paludina* beds were considered by Wahnschaffe (1909.1, pages 324, 325) as among the best instances in Germany of a warm interglacial fauna between the first and second drift sheets, namely, in First Interglacial time. These *Paludina* beds can be positively referred to the First Interglacial stage in question and definitely disprove Depéret's idea of a high-water sealevel in First Interglacial time. Wahnschaffe finds no evidence of disturbance and subsequent marine transgression in the *Paludina* beds; his work is the fullest and best general discussion of the "drift" of Germany that has been written.

(6) To sum up: (1) Leverett considers that Depéret's papers represent a zealous presentation of a theory which Depéret had conceived and regarded as new—a theory, however, which has not been overlooked by those who have devoted their lives to glacial and fluvial investigations; in other words, Depéret has been led to depend too much on coincidences in *altitude of terraces* and on the questionable assumption of very extensive eustatic movements. (2) The correlation paper of Brooks gives

definite data which lead us to question the applicability of Depéret's method of using the altitude of river terraces to settle questions of geologic age, since it furnishes a mass of data, both of the character of the interglacial deposits and the altitude relations, which demonstrate the inadequacy of terrace altitude relations to establish geologic and archeologic correlations.

(7) Brooks's discussion¹¹ of the Rhine terraces in the *Smithsonian Report* (pages 289, 290) gives data on the question of their gradient compared with that of the present stream. It appears that the slope of the oldest gravels is so rapid that they descend to and below the level of the gravels of the next or chief terrace. This chief terrace has the right height at Wesel and Bottrop to be consistent with Depéret's Milazzian stage, 54–60 meters above the stream; but on following it up the valley it is found at 73 meters at Duisburg, 90 meters at Düsseldorf, 106 meters at Keulen, and 136 meters at Bonn. It thus gets too high for the Sicilian stage of Depéret before reaching Bonn. On the other hand, the low terrace, which is only 5 meters above the river at Bonn, is 11 meters at Duisburg and still more above the stream at Weser and Dingden. What value has the Depéret method of classification on the Rhine? The chief terrace seems to have been built up at the close of the oldest glaciation of that region, which is interpreted to be the Second Glacial stage, for its gravel covers this old drift between Crefield and Nijmegen. This terrace is thus of the right age to be Milazzian, but it is only in the vicinity of Weser that it is of the right height to fit in with Depéret's altitude method.

(8) Leverett (in a letter of January 19, 1922) contributes a revision of the morainal lines of the "Middle Drift" [III] in Holland and western Germany; also of the next older drift [II], published in the map of Van Baren (1908). These lines have been inserted in the morainal map by Dr. Reeds (figure 3). In Leverett's paper of the "Comparison of North American and European Glacial deposits" (1910.1), he remarks that the "Middle Drift" has received very little attention by German geologists; they have never tried to map its limits; it is in fact a thin drift sheet, often 2 meters or less in thickness, which makes it difficult to determine the limits. Gagel omits the "Middle Drift," and by so doing has failed to establish the correlation. For example, he classes the underlying heavy sheet of the "Old Drift" as Third Glacial, but in all probability it is Second Glacial. The drift under the Paludinenbank in the vicinity of Berlin was correlated by Wahnschaffe with the First

¹¹ See Charles E. P. Brooks (1919.1) and Ellsworth Huntington (1922.1).

Glacial, but Gagel describes it as Second Glacial, and does not recognize any First Glacial in Germany. This, in Leverett's opinion, is an error. The matter of the extent of the Fourth Glacial drift in Germany is not fully settled, but there is an unanimous agreement that it extends much farther than the Baltic moraine, which J. Geikie considered as its limit. [Soergel (1919.1, figure 12, page 100) presents a map (figure 14) show-

Schematische Darstellung der
Maximalstände der einzelnen Phasen der letzten Eiszeit.

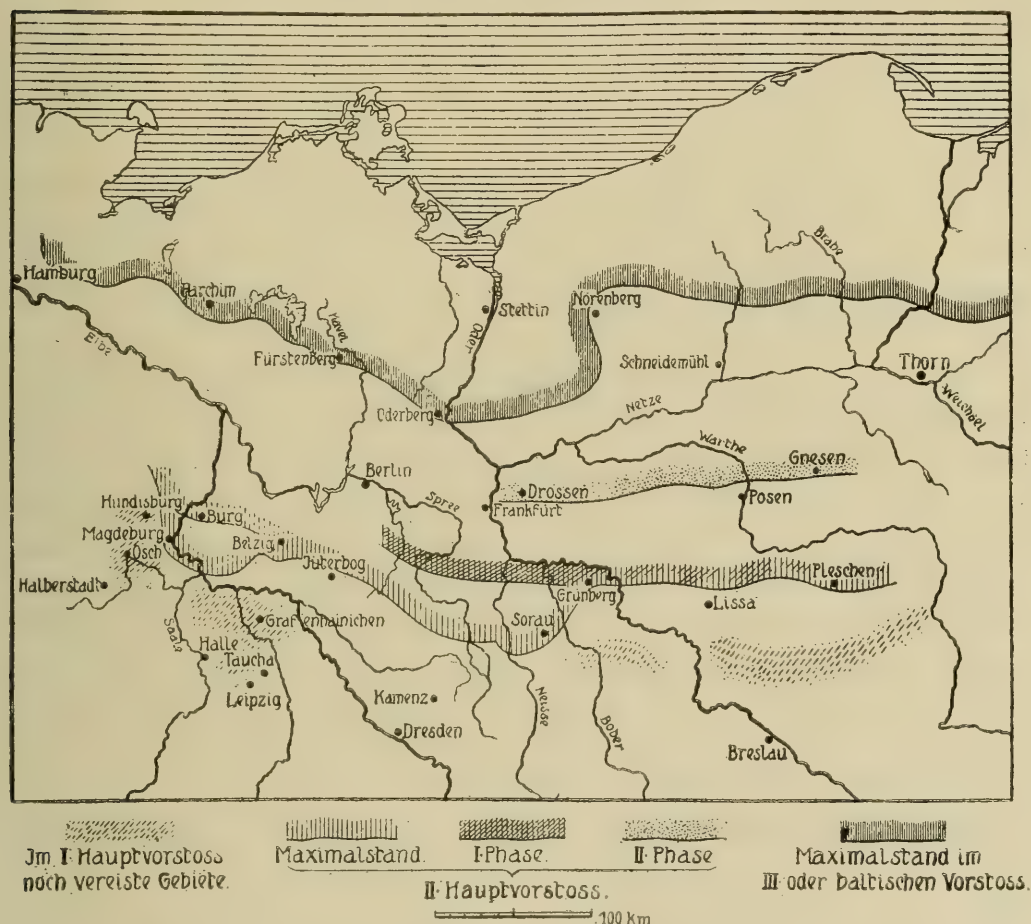


FIGURE 14.—Retreat Phases of the Fourth Glaciation in North Central Germany
After Soergel.

ing the stages which have been determined for the retreat of the ice of the Fourth Glaciation in north central Germany.] Leverett regards as very instructive the map in Werth's book, "Das Eiszeitalter," published in 1909, which sets forth four of the chief morainic systems of the Fourth Glaciation in Europe.

(9) Leverett considers that there is distinct advantage in the simple fourfold classification of the Ice Age, such as is presented in the Osborn-

Reeds' diagram (figure 13), but unfortunately there is in America the difficult "Iowan" question to complicate correlation; until this is settled, we do not know whether there were *four* or *five* glacial stages in America. Our last, or Wisconsin, stage is so complex that it is not an easy matter to correlate any part of it with the corresponding part of the Würm stage of Europe or with the last glaciation of the north of Europe. Leverett is unable to come to a definite opinion as to whether the Third Glaciation of Europe is the correlative of the Illinoian or of the Iowan of America; the drift of the Third Glaciation in Germany and in Holland is thin or scanty like our Iowan. This leaves the Second and First glaciations of Europe, which *seem* to correlate with the Second and First glaciations of America.

(10) Coming to the question of harmonizing Penck's interpretations with those of De Geer, Leverett is not clear as to the precise way in which the one interpretation would fit into the other. There is in this case the need for further careful field-work to clear up the matter satisfactorily. He states that he would not venture an opinion as to whether the morainic system which separates De Geer's "Gothiglacial" from his "Finiglacial" is the correlative of Penck's moraines of the Daun sub-stage, or whether the Daun moraines find their equivalent in later moraines of Sweden. It is unlikely that the Daun moraines are older than those which mark the division between Gothiglacial and Finiglacial in Sweden. In De Geer's "Quaternary sea bottoms in western Sweden" [and Antev's (1917.1) "Post-Glacial marine shell-beds in Bohuslän"] we have evidence of *remarkable diastrophic complexity*, which would serve to show the danger of following Depéret in his idea of simplicity of earth movements.

(11) Leverett notices that De Geer seems to think that his determination of 11,000 years for the time since the ice disappeared from the northern part of the Baltic region is inconsistent with the American estimate of over 30,000 years for the duration of Niagara Falls, and says it is perhaps four times too long. This leads Leverett to remark that it is likely that the ice in North America was reduced to a small area on the east side of Hudson Bay at the time it was melting out of the north end of the Baltic basin. In that case Niagara history is much longer. The part that corresponds to the life of Lake Algonquin would entirely precede it, and probably a considerable part of the life of Lake Nipissing. It seems to Leverett, therefore, that we are under no necessity of discarding the estimate of about 30,000 years for the life of Niagara. The estimate is, however, of a less refined nature than that made by De Geer, and is so understood by those of us who have followed Spencer and also

Taylor (1913.1) in the methods of making the estimates. Leverett is of the opinion that the Niagara estimates can not be more than 5,000, or at most 10,000, years out of the way; that the life of Niagara must have been at least 20,000 years, and that it may have been 35,000 to 40,000 years. The Niagara Falls Folio enables us to judge as to the quality of Taylor's work and the value of his estimates. Spencer's methods are brought out in his work on Niagara published by the Canadian Geological Survey.

(12) Leverett considers that, inasmuch as the ice of North America is likely to have been reduced to a small field in the part of Canada that is difficult of exploration, it may be some time, in the present sparsely settled conditions, before we can correlate the position of the ice with the Daun substage, or even with substages corresponding to the Gschnitz and the Bühl of Penck's classification. These may all be found in the wilds of Canada.

VIEWS OF WILLIAM C. ALDEN, OF THE U. S. GEOLOGICAL SURVEY

(13) William C. Alden agrees with Leverett (February 17, 1922) that it is not possible to substitute eustatic (sea movement) for diastrophic (land movement) as Depéret has done. While it is probably true that the net result of all crustal movements was downward, under gravity action, yet there have undoubtedly been upward earth movements both widespread and local; to these diastrophic movements Alden believes all changes of sealevel are attributable, except those actually due to the abstraction of water for storage in ice-sheets, and the subsequent return of the water to the sea-basins.

(14) As regards the beach levels, Alden remarks that it is very interesting to have the data brought together in the way Depéret has done, but that the results can not be regarded as final; nor is it probable that we can establish the Pleistocene classification on the basis of sea-beach levels. Only where direct connection is traceable between the glacio-fluvial terraces and the marine terraces might there be a basis for at least tentative correlation between the glacial and marine phenomena. There is an opportunity to test out the matter of correlating glacial and marine features right in the vicinity of New York, and it may be hoped that the coordination made by Depéret will be a stimulus to American glaciologists to work out the relations carefully.

VIEWS OF EMMANUEL DE MARTONNE AND DOUGLAS W. JOHNSON

(15) Emmanuel de Martonne writes March 29, 1922, in reply to a number of questions raised by Douglas W. Johnson, that he was at first

skeptical of the *eustatic* movement theory and of the conclusions reached by General de Lamothe, but that the studies of terrace and shoreline altitudes have multiplied in the last few years in the Mediterranean and France with such concordant results that one can not escape being impressed by them. Everywhere are found the terraces of 15–20 meters, 30–35 meters, 50–60 meters, and 90–100 meters. Everywhere are found the valley ways carved below the present level of the sea near mouths of great rivers and for a considerable distance upstream. Particularly striking are the observations of Gignoux (now professor in the University of Strasbourg), who has found in Italy that the levels of Depéret and de Lamothe are very well marked where there have been no recent dislocations. Chaput, although he was rather skeptical when he began his studies upon the terraces of the Loire, was convinced by the evidence, and found the 15 and the 30 meter level everywhere. There seems to be some question as to the upper levels in the Sahel of Algeria indicated by de Lamothe. In developing his theory, Depéret, it appears, has not been strict enough in the choice of evidence supporting the trace of the upper shorelines; that he is too systematically opposed to continental movements (diastrophism); that there are some contradictions in his argument. He considers the Saxonian (Second glaciation of the north) as the equivalent of the Mindelian (Second Alpine glaciation) and of the Milazzian (epoch of the shore of 55–60 meters, on the Mediterranean); but he tells of terraces of 33 meters referred to the Saxonian.

(16) There is something rather astonishing in the statements of Depéret about the altitudes of cold and warm faunas; for example, the deposits with *Yoldia arctica* at —13 meters, near Hamburg, would be contemporaneous with those of the warm fauna of Neudeck at +100 meters, the first being formed at the bottom of the sea, which was cold, the second near the shore; so that the deposits with *Yoldia* which one finds at sealevel in England, would indicate an old shore of +100 meters. . . . However, when Depéret defines the shore of 100 feet (33 meters), as later than the Polonian (Third glaciation of the north), it is by the deposits with *Yoldia* which are at this altitude.

(17) De Martonne recognizes difficulties in the application of the eustatic theory. The lowering of sealevel must be very rapid, being due to the sinking of submarine depths; but the rising of the water must be very slow, since it is due to sedimentation; the result is that the shoreline, during the transgression, must be constantly displaced. Depéret notes, however, after the regression below present sealevel, an uplift of +33 meters, which maintains itself at this level during two glacial periods and an interglacial period at least. Concerning the Côtes de

Provence, with which de Martonne is acquainted, it appears that there is in this region, as in Algeria, a very constant littoral terrace at 15 meters, visible on all the promontories, which he attributes to marine abrasion; also that shore deposits have been found in place there. There are also indications of higher levels, but these are not very clear. According to de Martonne, the terraces of the valley of the Rhone and that of the Durance are more numerous than de Lamothe and Depéret say, and are manifestly influenced by glaciers; but it is not true, as Penck says and as de Martonne states that he himself has believed at times, that they all join downstream. There are, particularly near the delta of the Rhone, some very high terraces. De Martonne has not personally studied the famous grotto of Baoussé Roussé near Monaco, where there are human remains, but he has confidence in Boule's very searching monograph, the conclusions of which are favorable to displacements of the sealevel.

(18) De Martonne sums up as follows: We can not deny modifications of sealevel since Pliocene time, but they may be attributable to earth movements (diastrophic), not only regressive but transgressive; nor are these earth movements limited to sea-bottoms. The result is that we can not find everywhere shorelines at the same levels. There is, without doubt, much to accept and much to abandon in the argument advanced in favor of the eustatic theory, but the observations are too numerous not to make a strong impression. We must remain capable of giving fair consideration to earth movements (diastrophism) and to changes in sealevel due to the accumulation and the melting of glaciers.

(19) Professor Johnson doubts whether the eustatic theory of a rise and fall of sealevel, advocated by de Lamothe and supported in part by Depéret and Gignoux, can adequately explain the elevated marine shorelines, marine terraces, and river terraces, attributed to the Pliocene and Pleistocene periods, occurring at successive elevations on the shores of the Mediterranean and Atlantic and along the rivers of Europe and northwestern Africa. His own observations in America and Europe do not indicate the existence of a fairly definite series of marine terraces and river terraces, at more or less uniform elevations above the present sealevel and present river channels, either on the shores of the Atlantic or in parts of the Mediterranean seen by him; and he accordingly believes, with the majority of geologists, that differential movements of the land, together with the normal degrading of alluvium-filled valleys, better account for the observed facts. [Johnson inclines rather to the diastrophic theory. It appears from the above résumé of opinion that the new classification of the Quaternary proposed by Depéret is being

received with doubt chiefly because the assumption of *uniform eustatic movements*, on which it is based, is not regarded as yet demonstrated.]

DISCUSSION BY FRANK LEVERETT

In a revised discussion, dated February 6, 1922, Leverett comments as follows: (1) Depéret refers the changes in the (eustatic) altitude of the marine shores to a rise and fall of the sea instead of a rise and fall of the land or diastrophism; he thus confidently correlates shorelines of a given height, no matter where they occur in Europe and in Africa; by this method he makes a correlation without the essay of a continuous tracing across the intervening space; with the exception of Scandinavia, and certain local areas on the Mediterranean, he finds no occasion to calculate differential uplift of the earth; also, where shorelines occur at various other altitudes than those of the main ones of the type area (as is sometimes the case), he rules them out as of minor rank. (2) Similarly, the assumption is made by Depéret that if a stream has lowered its bed a given amount, it is in response to a lowering of the sea, and that, too, no matter how far from the sea the lowering may occur or what the size of the stream. He assumes that a mature profile of equilibrium is constantly maintained during the lowering. But a stream really acts very differently when its mouth is lowered. The deepening begins at the mouth and works back gradually headward. This is well shown in the Allegheny River drainage of western Pennsylvania. Because of the enlargement of its drainage area, in the Kansan (or Second) stage of glaciation, the valley has been greatly deepened, but is still far from being down to a profile of equilibrium, its rate of fall being three times as great as that of the Monongahela. The lowering of the main stream has caused the tributaries to begin cutting down at their mouths, and the deepening is gradually working headward. Yet even now, after the lapse of perhaps a half million years, the deepening has had time to reach scarcely two-thirds the way to their sources. See Chamberlin and Leverett, *American Journal of Science*, April, 1894, pages 261, 262; also I. C. White, *American Journal of Science*, volume 34, 1887, page 378. (3) Depéret also takes no account of the blocking of valleys by drift accumulations in the glaciated regions, and the relatively small amount of work required to remove some of these drift barriers, and thus effect a notable lowering that is independent of any change in the level of the sea into which the stream discharges. In this way a stream may lower its bed very materially in a single stage of glaciation. The terraces at 55-60 meters, and those at about 30 meters, on the Rhone in the vicinity of Lyons, may thus be related to drift barriers, and if so

may easily fall in a single stage of glaciation. This, however, is not Depéret's idea, for he makes the higher terrace fall in the Second Glaciation and the lower in the Third. He thus discards Penck's interpretation, that only the Third Glaciation, or Riss drift, is here represented. His difference is based on altitude alone, regardless of the degree of preservation of moraines. From his study of the moraines of that region, in 1908, Leverett is of the opinion that they exhibit the degree of preservation that characterizes the moraines of the Third, or Riss, Glaciation at various other points on the border of the Alps, and are much better preserved than those of the Second, or Mindel, Glaciation.

(4) In the interpretation of the features in Germany, Depéret takes no account of the work of the most experienced glacialists, such as Wahnschaffe, Keilhack, and Gagel, but makes use of data prepared by Geinitz, an extreme monoglacialisist. Then, as a result of forced coordination, on the basis of altitudes of beaches of the Mediterranean, he erroneously gives the sea of the First Interglacial stage a higher altitude in Germany, where it has been shown by Wahnschaffe (1909.1, pages 324, 325) to have had a low altitude.

(5) On the main proposition, of a similar Glacial succession in the Alps and in northern Europe, Depéret's coordination is likely to stand. The other coordinations are likely to be of value in stimulating a critical investigation of river terraces in relation to marine shorelines, to the glaciations, and to the human prehistory. Taken as a challenge to field workers, they may thus have much value.

DISCUSSION OF THE EUSTATIC THEORY BY PROF. W. M. DAVIS

In so far as the conclusions of the foregoing paper of Osborn and Reeds are based on de Lamothe's interpretation of certain Algerian and European terraces by *eustatic* changes of ocean level which must be world wide, instead of by *epirogenic* changes in the earth's crust which may be local, Davis believes they are questionable, because de Lamothe did not precede his interpretation by a competent discussion of the evidence by which eustatic changes can be distinguished from *epirogenic* changes. De Lamothe appears to have concluded that, if certain marine terraces on the south side of the Mediterranean run at about constant levels with about constant intervals for a certain distance, and correspond in interval to certain river terraces in Europe, then the level of ocean and not of lands must have been changed.¹² In examining that con-

¹² See his various essays in the Bulletin de la Société Géologique de France for 1899, 1901, 1904, 1905, and 1912, particularly an article: . . . "Terrasses des vallées de l'Isser (Algiers), de la Moselle, du Rhine et du Rhone . . . 1, 1901, 297-383, especially pages 350, 382.

clusion, we shall do well to follow Gilbert's advice and "go behind the postulates"; especially behind the postulates that a considerable stretch of a continental coast can not rise equably, and that terraces separated by similar vertical intervals in the valleys of different rivers at a considerable distance inland from the river mouths indicate eustatic changes of ocean level. De Lamothe's treatment of the river-terrace half of his problem is far from satisfactory, because it seems tacitly to assume that the fall or grade of a river is constant during successive epochs of aggrading and degrading its valley, and this is altogether improbable.

As to the coastal half of the problem, no thorough and competent inquiry has yet been made by de Lamothe or any one else. No one has yet determined how large a fraction of the entire length of all continental and insular coastlines ought to exhibit shoreline terraces at given heights above sealevel standard, in the sense that each terrace represents everywhere the same time measure of abrasional or depositional work, allowance being made for nature of coastal rocks, outline of coast, and exposure to wave action where terraces are cut, and for area drained where delta terraces are built, in order to warrant the conclusion that coasts thus terraced have stood still and the ocean level has changed. It is easy to conceive that if a part of the ocean floor first rose and then sank while all the coasts and islands of the world stood still, a temporary high-level shoreline would now constitute a coastal terrace everywhere at a uniform altitude above present sealevel, and that all river valleys should show appropriate effects of stream-filling and erosion. It is also easy to conceive that if the disturbed ocean-floor area which rose and sank were extended to include part of a continental border, then that part of the continental border would not be terraced like the rest of the coasts of the world.

It is, furthermore, easy to imagine that if some such fraction as nine-tenths of the coasts of the world exhibited a standard terrace everywhere at the same altitude (the corresponding features of river valleys are here left unmentioned, to save space), while the remaining tenth exhibited no such terrace, then the ocean and the non-terraced coastal tenth must have changed while the nine-tenths remained fixed. But it is absolutely unwarranted in the present state of exploration of the world's coasts—one might almost say in the present state of mental equipment for such exploration—to assert that a large share of the world's coasts possesses a standard terrace; and until such an assertion can be safely made, the assumption of eustatic instead of epirogenic change is unjustified. For example, if such an assertion be based on the occurrence of a terrace along several hundred miles or even along one or two thousand miles

of coastline, while scores of thousands of coastline miles elsewhere exhibit higher or lower terraces, then the assertion involves the assumption that while the coasts having the standard terrace have stood still, all the oceans and all the other coasts of the world have moved; and that seems unreasonable.

De Lamothe appears to have followed Suess¹³ in a preference for eustatic over epirogenic changes. Important as was the analysis of the earth's framework by the great Austrian geologist, Davis believes that certain of his conclusions regarding eustatic changes are valueless. For instance, he based his belief in a recent and general sinking of ocean level upon the reported occurrence of various elevated coral reefs, none of which, he thought, had a greater altitude than 100 meters over present sealevel; and he appears to have supported this belief by accepting the occurrence of marks of marine action at a similar altitude on many continental coasts in various latitudes, without inquiring whether all the marks are of the same time value or not. But most of the coasts of the world have not been shown to possess such uniform marks of marine action; and as to elevated coral reefs, they not only stand at very unlike altitudes, varying from five or ten to over 1,000 feet, but they exhibit great differences in the amount of erosion they have suffered since their emergence.

Davis concludes:

"I am much interested in reaching a correct understanding of their behavior, whatever it was, and I therefore emphasize the belief that what is now needed in this problem is a critical discussion of the evidence on which a correct understanding can be reached. In this particular case, I question the validity of de Lamothe's conclusions because his discussion of that evidence is altogether unconvincing; he does not establish his postulates; indeed, he hardly states what his postulates are. De Lamothe appears to trust entirely the fact that the altitudes of marine and river terraces over a certain distance along the southern coast of the Mediterranean show a fair measure of accordance with the vertical spacing of certain river terraces in Europe; he does not inquire whether similar coastal and river terraces occur elsewhere. To de Lamothe, the area of uncertainty in his problem is not like a broad upland with plenty of space for continued inquiry during a period of suspended judgment, but like a very narrow ridge or fence, on which he cannot remain in comfort and from which he therefore must descend into one of the two alternative fields. The development of new conclusions from an asserted conclusion thus reached is unwise."

¹³ *Das Antlitz der Erde*, 1888, ii, 399, 401, etc.

IV. BIBLIOGRAPHY

ANTEVS, ERNST:

- 1917.1. Post-glacial marine shell-beds in Bohuslän. *Geol. Fören. Förhandl.*, Band XXXIX, Heft IV, April, pages 247-425, figures 1-8.

BARROIS, CHARLES:

- 1897.1. Sur l'extension du Limon Quaternaire en Bretagne. *Ann. Soc. Géol. du Nord*, tome XXVI, pages 33-44, plate I.

BISHOP, A. HENDERSON:

- 1913-1914. An Oransay shell-mound—a Scottish pre-Neolithic site. *Proceedings of the Society Antiq. of Scotland*, volume XLVIII, pages 52-108, figures 1-44.

BOULE, MARCELLIN:

- 1888.1. Essai de Paléontologie stratigraphique de l'Homme. *Revue d'Anthropologie*, 1888, (3), III, pages 129-144, 272-297, 385-411, 647-680.
- 1921.1. Les hommes fossiles. *Éléments de Paléontologie Humaine*. Masson et Cie, Paris, octavo.

BROOKS, CHARLES E. P.:

- 1919.1. The correlation of the Quaternary deposits of the British Isles with those of the continent of Europe. *Annual Report of the Smithsonian Institution for 1917*, pages 277-375.
- 1921.1. The evolution of climate in north-west Europe. *Quarterly Journal of the Royal Meteorological Society*, number 199, volume 47, 1921, pages 173-194. London.

BRÜCKNER, EDUARD:

- 1921.1. Geochronologische Untersuchungen über die Dauer der Post-glazialzeit in Schweden, in Finnland und in Nordamerika. *Zeitschrift für Gletscherkunde*, Band XII, Heft 1-2, July, 1921, pages 39-57, figures 1-5.
- See Penck, A., and Brückner, E.

CHAMBERLIN, T. C.:

- 1907.1. *Geology*, volume III. (With Salisbury, R. D.) Henry Holt & Co., New York.

CHAPUT, E.:

- 1917.1. Recherches sur les Terrasses Alluviales de la Loire et de ses Principaux Affluents. *Ann. Univ. de Lyon*, 1917, new series, 1, Fasc. 41, pages 306, plates I-III, text figures 1-23, chart.
- 1921.1. Observations sur les Alluvions Anciennes de la Seine. *Compte Rendu Académie des Sciences*, January 3, 1921, tome 172, pages 77-79.

COMMONT, V.:

- 1906.1. Les découvertes récentes à Saint-Acheul, l'Acheuléen. *Revue de l'Ecole d'Anthropologie*, Paris, année XVI, 1906, pages 228-241.
- 1908.1. Les industries de l'ancien Saint-Acheul. *L'Anthropologie*, tome XIX, 1908, pages 527-572.

- 1909.1. L'industrie moustérienne dans la région du nord de la France. Congrès Préhistorique de France, Ve session, 1909, pages 115-157.
- 1909.2. Saint-Acheul et Montières. Notes de géologie, de paléontologie et de préhistoire. Mém. Soc. Géol. du Nord, tome VI, iii, 68 pages, 3 plates.
- 1910.1 Note préliminaire sur les Terrasses fluviales de la Vallée de la Somme. Ann. Soc. Géol. du Nord, tome XXXIX, pages 185-210.
- 1912.1. Chronologie et Stratigraphie des industries Protohistoriques, Néolithiques et Paléolithiques dans les Dépôts Holocènes et Pleistocènes du Nord de la France et en Particulier de la Vallée de la Somme. Congr. Intern. d'Anthropol. et d'Archéol. préhist., Compt. Rend., XIV^e session, Genève, 1912, pages 239-254.
- 1912.2 Moustérien à faune chaude dans la vallée de la Somme à Montières-les-Amiens. Congr. Intern. d'Anthropol. et d'Archéol. préhist. Compt. Rend., XIV^e session, Genève, 1912, pages 291-300.
- 1914.1. Les hommes contemporains du Renne dans la Vallée de la Somme. Mém. Soc. Antiq. de Picardie, tome XXXVII. Amiens, 1914, pages 209-646 and map.
- 1916.1. Les terrains quaternaires de tranchées du Nouveau Canal du Nord. L'Anthropol., 1916, volume 27, pages 309-314; 517-538.

CROLL, JAMES :

- 1875.1. Climate and time in their geological relations. D. Appleton & Co., New York.

DALY, REGINALD :

- 1915.1. The Glacial-control theory of coral reefs. Proceedings of the American Academy of Arts and Science, volume 51, number 4, pages 158-251.
- 1920.1. A general sinking of sealevel in recent time. Proceedings of the National Academy of Sciences, volume 6, number 5, May, 1920, pages 246-250.
- 1920.2. A recent worldwide sinking of ocean-level. Geological Magazine, volume LVII, June, 1920, pages 246-261.

DE GEER, GERARD :

- 1910.1. Geochronology of the last 12,000 years. Congr. Géol. Intern., Compt. Rend., XI session, pages 241-253, plates I, II.
- 1921.1. Correlation of late Glacial annual clay-varves in North America with the Swedish time scale. Geol. Föreningens, Band XLIII, number 344, Häfte 1-2, January-February, 1921, pages 70-73.

DE LAMOTHE, LÉON :

- 1899.1. Note sur les Anciennes Plages et Terrasses du Bassin de l'Isser et de Quelques Autres Bassins de la Côte Algérienne. Bull. Soc. Géol. de France, Sér. 3, tome XXVII, 1899, pages 257-303, plate III.
- 1901.1. Sur le Rôle des Oscillations Eustatiques du Niveau de Base dans la Formation des Systèmes de Terrasses de Quelques Vallées. Compt. Rend. Acad. Sci., Paris, tome 132, 1901, pages 1428-1430.

- 1911.1. Les Anciennes Lignes de Rivage du Sahel d'Alger et d'une Partie de la Côte Algérienne. *Mém. Soc. Geol. de France* (4), tome I, 1911, 288 pages, 3 plates.
- 1916.1. Les Anciennes Lignes de Rivage du Bassin de la Somme et Leur Concordance avec Celles de la Méditerranée Occidentale. *Compt. Rend. Acad. Sci., Paris*, tome 162, pages 948-951.
- 1918.1. Les Anciennes Nappes Alluviales et Lignes de Rivage du Bassin de la Somme et Leurs Rapports avec Celles de la Méditerranée Occidentale. *Bull. Soc. Géol. de France* (4), tome XVIII, pages 3-58.

DEPÉRET, CHARLES:

1908. The evolution of Tertiary mammals and the importance of their migrations. *American Naturalist*, volume XLII (translation).
- 1908.1. First paper, Eocene Epoch, volume XLII, number 494. February, pages 109-114.
- 1908.2. Second paper, Oligocene Epoch, volume XLII, number 495, March, pages 166-170.
- 1908.3. Third paper, Miocene Epoch, volume XLII, number 497, May, pages 303-307.
- 1909.1. The transformations of the animal world. *International Science Series*, edited by F. Legge. London, 1909.
- 1918-1920. Essai de coordination chronologique générale des temps quaternaires. *Compt. Rend. Acad. Sci., Paris*.
- 1918.1. Tome 166, March 25, 1918, pages 480-486.
- 1918.2. Tome 166, April 22, 1918, pages 636-641.
- 1918.3. Tome 166, June 3, 1918, pages 884-889.
- 1918.4. Tome 167, September 16, 1918, pages 418-422.
- 1918.5. Tome 167, December 16, 1918, pages 979-984.
- 1919.1. Tome 168, May 5, 1919, pages 868-873.
- 1920.1. Tome 170, January 19, 1920, pages 159-163.
- 1920.2. Tome 171, July 26, 1920, pages 212-218.
- 1921.1. La Classification du Quaternaire et Sa Corrélation avec les Niveaux Préhistoriques. *Compt. Rend. Géol. Soc. de France*, number 9, pages 125-127.

GAGEL, C.:

- 1913.1. Die Beweise für eine Mehrfache Vereisung Norddeutschlands in diluvialer Zeit. *Geologische Rundschau*, Band IV, pages 319-362, 444-502, 588-591.

GEIKIE, JAMES:

- 1894.1. The Great Ice Age. Third edition.
- 1914.1. The antiquity of man in Europe, pages i-ix, 1-328, plates I-XXI, text figures 1-9, 4 maps.

GIGNOUX, MAURICE:

- 1913.1. Les Formations Marines Pliocènes et Quaternaires de l'Italie du Sud et de la Sicile. *Ann Univ. de Lyon*, 1913, new series, I, Fasc. 36, pages i-xxiv, 1-693, plates I-XXI, text figures 1-42.

HARMER, F. W.:

- 1906.1. The glacial deposits of the east of England. *Geological Magazine*, London, Decade V, new series, III, 1906, pages 468-470.

1906.2. Lake Oxford and the Goring Gap. *Geological Magazine*, London, Decade V, new series, III, 1906, pages 470-472.

1910.1. The glacial geology of Norfolk and Suffolk. *Transactions of the Norfolk and Norwich Naturalists' Society*, volume IX, pages 108-133, figures 1-7, map.

HUNTINGTON, ELLSWORTH :

1922.1. The evolution of climate in northwestern Europe: A review [of C. E. P. Brooks' paper of same title, 1921.1]. *Geographical Review of American Geographic Society*, New York, volume XII, number 1, January, 1922, pages 126-130.

LEVERETT, FRANK :

1910.1. Comparison of North American and European glacial deposits. *Zeitschr. für Gletscherkunde*, Band IV, Heft 4, June, 1910, pages 241-295, Taf. I-V, figures 1-5; Heft 5, July, 1910, pages 321-342. With supplementary note, Band V, Heft 4, April, 1911, pages 315-316.

MAYET, LUCIEN :

1921.1. Division Géologique du Quaternaire et Niveaux Archéologiques Paléolithiques. *Bull. Soc. Préhist. Française* (reprint), pages 1-6, diagram.

1921.2. Correlations Géologiques et Archéologiques de Temps Quaternaires. *Compt. Rend. Assn. Française Advance. Sci.*, pages 481-490.

MAYET, LUCIEN, and PISSOT, J. :

1915.1. L'Abri-sous-Roche Préhistorique de La Colombière, près Poncin (Ain), 206 pages, 25 plates, 102 text figures. *Ann. Univ. de Lyon*, series I, volume 39.

MONTÉLIUS, OSCAR :

1920.1. Paleolithic implements in Sweden. *Antiquaries Journal*, London, pages 98-104.

OBERMAIER, HUGO :

1909.1. Les Formations Glaciaires des Alpes et l'Homme Paléolithique. *L'Anthropol.*, tome XX, 1909, pages 497-522.

1912.1. *Der Mensch der Vorzeit*. München, royal octavo, 1912.

1916.1. *El Hombre Fósil*. Com. Investig. Paleont. y Préhist., Mem. No. 9. (For translation, as "Fossil Man in Spain," see footnote, page 445.

OSBORN, HENRY FAIRFIELD :

1910.1. The age of mammals in Europe, Asia, and North America. Macmillan Co., New York, octavo, 1910.

1915.1. Review of the Pleistocene of Europe, Asia, and Northern Africa. *New York Academy of Sciences*, volume XXVI, July 30, 1915, pages 215-315, 20 text figures.

1915.2. Men of the Old Stone Age, their environment, life, and art. Scribner's, New York, octavo, November 24, 1915, 545 pages, plates I-VIII, 268 text figures. Third edition, 1918, pages i-xxviii, 1-559, plates I-VIII, 275 text figures.

PENCK, A., and BRÜCKNER, E.:

1908.1. Das Alter des Menschengeschlechts. *Zeitschrift für Ethnol.*, Jahrgang 40, Heft 3, 1908, pages 390-407.

1909.1. Die Alpen im Eiszeitalter, volumes I, II, III. Leipzig, royal octavo, 1909. (This work appeared in eleven installments during the years 1901 to 1909.)

PISSOT, J.:

See Mayet, Lucien, and Pissot, J.

PUYDT, MARCEL DE, HAMAL-NANDRIN, J., and SERVAIS, JEAN:

1912.1. Liège Paléolithique. Le Gisement de Sainte-Walburge dans le Limon Hesbayen. *Bull. Inst. Archéologique Liégeois*, tome XLII, 1912, pages 139-215, 6 plates, 88 text figures.

SAURAMO, MATTI:

1918.1. Geochronologische Studien über die Spätglaziale Zeit in Südfinnland. *Bull. Commis. Géol. de Finlande*, tome IX, number 50, plates I-IV, text figures 1-5, pages 1-44.

SCHUCHERT, CHARLES:

1910.1. Paleogeography of North America. *Bulletin of the Geological Society of America*, volume 20, pages 427-606, plates XLVI-CI, February, 1910.

SOERGER, W.:

1919.1. Löss, Eiszeiten und Paläolithische, pages I-IX, 1-177, 14 text figures, chart. G. Fischer in Jena, 1919.

SUESS, EDUARD:

1883.1. Das Antlitz der Erde, volumes I, II, III (1883-1909). (Authorized English translation by Sollas and Sollas, 1904-1909.)

TAYLOR, FRANK B. (and E. M. KINDLE):

1913.1. Niagara Folio, number 190, New York. *Geological Atlas of the United States*. U. S. Geological Survey, Washington, D. C.

VAN BAREN, JAMES:

1908.1. Der Morphologische bau des Niederländischen Diluviums Nördlich vom Rhein. *Compte Rendus des Travaux*, IX Congrès International Geogr., Genève, tome II, pages 143-148, map and plate.

VAYSON, ANDRÉ:

1920.1. La Plus Ancienne Industrie de Saint-Acheul. *L'Anthropologie*, tome XXX, 1920, pages 441-496, plates I-XVI, text figures 1-16.

VIRCHOW, HANS:

1920.1. Die menschlichen Skeletreste aus dem Kämpfe'schen Bruch im Travertin von Ehringsdorf bei Weimar. Jena, 1920.

WAHNSCHAFTE, FELIX:

1909.1. Die Oberflächengestaltung des Norddeutschen Flachlandes. 3d edition, J. Engelhorn, Stuttgart, 1909. 405 pages, with 24 plates and 39 text figures.

WRIGHT, W. B.:

1914.1. The Quaternary Ice Age. Macmillan and Co., London, 1914. pages i-xxiv, 1-464, 23 plates, 155 text figures.

STAGES OF THE ICE AGE ¹

BY WARREN UPHAM

(Presented before the Society December 28, 1921)

CONTENTS

	Page
Sequence of glacial and interglacial stages.....	491
Nebraskan glaciation.....	493
The Aftonian interglacial stage.....	495
Kansan glaciation.....	499
The Yarmouth interglacial stage.....	503
Illinoian glaciation.....	504
The Sangamon interglacial stage.....	505
Iowan glaciation and loess deposition.....	506
The Peorian interglacial stage.....	506
Wisconsin glaciation.....	507
The Champlain stage.....	510
Estimated time ratios.....	512

SEQUENCE OF GLACIAL AND INTERGLACIAL STAGES

Throughout the Glacial period of growth, culmination, and decline of the North American and European ice-sheets, the climate causing the snowfall and ice accumulation fluctuated to such an extent that the boundaries of the continental glaciation were alternately advanced and checked or drawn back.

North America had five stages of widely extended icefields. First was the long time of Nebraskan glaciation, followed by a great recession of the ice-borders during an interglacial stage named Aftonian, from its stratified beds and fossils near Afton, in southwestern Iowa. The second and maximum extension of ice accumulation is named, in the Keewatin area of its outflow west of the Mississippi, the Kansan stage, which was broken by the Yarmouth interval of ice melting and retreat. With the Kansan glaciation, but in part spreading across the eastern edge of its

¹ Manuscript received by the Secretary of the Society December 12, 1921.

drift sheet and melting later from the Mississippi, was the third, or Illinoian, icefield, belonging to the far extended Labradorian area of glacial outflow. After the Kansan and Illinoian stages, which appear to have been mainly contemporaneous, another retreat of the ice-sheet took place in the Sangamon interglacial stage. Both the Yarmouth and Sangamon areas of wavering glaciation, and the duration of their stages, were slight in comparison with the Aftonian stage, which was the most prolonged interruption of the Ice Age on this continent.

Next were the Iowan and Wisconsin stages of glaciation, the fourth and fifth in the list of wide climatic fluctuations that successively amassed and melted back the North American icefields. The Iowan drift was followed by the chief deposit of the loess, a peculiar silt, which was weathered and eroded in the vicinity of Peoria, in Illinois, previous to the re-advancing Wisconsin glaciation. Hence the name Peorian is applied to the interglacial time of recession of the ice-border between these stages of colder climate and ice-advance. Depression of the land during the Iowan glacial stage had given decreased slopes of the Missouri, Mississippi, and Ohio valleys, permitting them to receive the thick formation of the loess. The land subsidence appears to have remained, or even to have progressed for the northeastern part of our continent, during the Wisconsin stage, while the most prominent marginal moraines were amassed at times of pause or often some readvance that accompanied the general melting and final departure of the ice-sheet.

After the ice had melted far back, the sea covered the depressed coast and reached inland along the Saint Lawrence, Ottawa, and Lake Champlain valleys, forming fossiliferous marine beds, from which this latest and relatively short part of the Glacial period is named the Champlain stage. It is thus seen that the alternating Iowan, Peorian, Wisconsin, and Champlain stages, comprising the time of greatest subsidence of the continental glaciated area, were attended by the growth, fluctuations, and disappearance of the Iowan and Wisconsin icefields. These four late stages seem to have been somewhat closely continuous with the preceding Kansan and Illinoian maximum glaciation, which was widely separated from the Nebraskan stage by the Aftonian retreat of the ice boundaries.

A similar sequence of glacial and interglacial stages has been traced in the British Isles, northern Europe, and the Alps, which indicates that the climatic conditions producing the Ice Age on the continental areas at opposite sides of the Atlantic were approximately contemporaneous, and that their fluctuations of glaciation were caused by like secular changes of climate.

NEBRASKAN GLACIATION

The earliest recognized stage of great extension of the ice-sheet upon Canada and the United States has been named Albertan and Jerseyan, from its drift in Alberta and New Jersey. Following a suggestion of the late Prof. Samuel Calvin, the preferable name Nebraskan was proposed by Prof. B. Shimek² for this stage. Thus all the series of North American ice advances and recessions, if the Champlain stage be excepted, are named from the glacial drift and alternating interglacial beds within the drainage basin of the Mississippi.

Eroded river valleys have occasional exposures of Nebraskan drift, beneath the Kansan drift and formations of Aftonian age, in eastern Nebraska and in southern and eastern Iowa; but its most western and southern extension in that region was probably everywhere overspread and surpassed by the Kansan icefield.

East of the Mississippi the early Patrician transportation of copper fragments and drift boulders from the region of Lake Superior to central and southern Ohio seems referable to the Nebraskan stage of glaciation; Belonging originally to Patrician drift, but later carried onward as a part of the Illinoian drift, Prof. G. F. Wright found boulders of red jasper conglomerate near Cincinnati, borne beyond the Ohio River into the north edge of Kentucky, where they were deposited at the extreme boundary of the ice-sheet after a southward glacial journey of about 500 miles from their parent ledges, east of Lake Superior and north of Lake Huron.

In northeastern Pennsylvania and northern New Jersey the attenuated border of the drift, extending 10 to 25 miles south of the terminal moraine, is referred by Chamberlin and Salisbury to the first great stage of our continental glaciation, named by them Jerseyan, probably correlative with the Nebraskan stage and the ancient Patrician drift. It is remarkably contrasted with the adjoining drift sheet of Wisconsin age, which includes the thick moraine and spreads thence far north upon New York, New England, and eastern Canada. The thin Jerseyan drift remains in patches, and indeed it may have been originally so deposited. Formed mainly by the local snowfall, the thin border of the early icefield probably had low surface slopes, without sufficient movement in many portions for drift erosion, transportation, and deposition.

Reaching more than 1,200 miles from the Missouri River to the Atlantic close south of New York City, the southern margin of the most ancient known stage of our continental glaciation fell not very far short of the later maximum icefield in Kansas and Missouri. It attained nearly

² Bulletin Geol. Soc. of America, vol. 20, December 24, 1909, p. 408; also in *Science*, January 14, 1910.

the same limit as the Illinoian and Ohio drift, which was early borne southward from the Patrician central area of outflow, but later from the more eastern Labradorian area. On the southwest edge of the very broad Quebec lobe of that eastern icefield, from the reentrant angle of the glacial boundary near the east end of Lake Erie to the coast of New Jersey, the earliest drift extends beyond the latest Wisconsin glaciation, which is bordered by a belt of prominent morainic ridges and hills.

With so great southward extension of the ice-sheet in the Nebraskan stage on the east half of our continent, it doubtless covered nearly all of Minnesota and the upper part of the Mississippi basin, excepting the large driftless area, mostly in Wisconsin, which was exempt from glaciation through all the Ice Age.

Across the Canadian provinces of Saskatchewan, Alberta, and British Columbia, and over the adjoining border of the United States, the Keewatin and Cordilleran icefields probably reached nearly as far south in Nebraskan time as in any of the later and shorter stages of glaciation. For that western half of the continent, through the admirable studies of Gilbert and Russell on Lakes Bonneville and Lahontan in Utah and Nevada, and from the Quaternary history of Lake Mono, in California, it is ascertained that the somewhat moister climatic conditions producing the remarkable enlargement of the lakes in the Great Basin were attended with increased snowfall and glaciation upon the contiguous mountain ranges. The two stages of great rise of these lakes in the Pleistocene period, separated by the intervening stage of their desiccation, when they were nearly or wholly evaporated away, are very certainly correlative on more northern and eastern parts of this continent with two divisions of the Ice Age that were marked by abundant snowfall and ice accumulation, while the interval of desiccation has its analogue eastward in an interglacial stage of fluctuating retreat and readvance of the ice boundary. Gilbert wrote of Lake Bonneville as follows, noting the parallelism of its history with climatic changes that gave alternate stages of growth and decline of glaciers and icefields:³

"The Bonneville basin originated by distortion of the earth's crust, and came into existence long before the Bonneville epoch. Little is known of its earliest climatic and physical conditions, but it was comparatively dry for a long period immediately preceding the formation of the great lake. During this period, alluvial cones were formed about the bases of all its greater mountain ranges, and the smaller ranges were wholly or partly buried by valley deposits. The valley deposits may have been entirely alluvial, but were probably also partly lacustral, the lakes being of small extent.

³ U. S. Geol. Survey, Monograph I, 1890, pp. 316-318.

"There followed two epochs of high water, with an interval during which the basin was nearly or quite empty. The first of these epochs was at least five times as long as the second. The second scored its water mark 90 feet higher than the first, and would have encroached still farther on the basin sides had it not been checked by outflow. During the epoch of outflow, the discharging current eroded the rim, and thus lowered the lake 375 feet; and after the outflow had ceased, the water fell by desiccation, with one notable interruption, to its present level in Great Salt Lake. The inter-Bonneville epoch of low water was of greater duration than the time that has elapsed since the final desiccation.

"The history of the Bonneville oscillations is, moreover, closely paralleled by that of the Lahontan oscillations, and it is believed that they belong to a series of climatic changes affecting not only these two basins, but the adjacent subdivisions of the Great Basin. . . .

"The moraines of three Pleistocene glaciers descend from the Wasatch Mountains to the level of the Bonneville shoreline; the moraines of four glaciers descend from the Sierra Nevada to the level of the old shoreline of Mono Lake; and the relations of these moraines to the shores of the lakes and the associated deposits indicate that the maximum stage of the lakes coincided closely with the epoch of maximum glaciation.

"The phenomena sustain the theory that the Pleistocene lakes of the western United States were coincident with the Pleistocene glaciers of the same district, and were produced by the same climatic changes. It follows as a corollary that the glacial history of this region was bipartite, two maxima of glaciation being separated, not by a mere variation in intensity, but by a cessation of glaciation."

Comparing the fluctuations of the western lakes and glaciers with those of the North American ice-sheet, we may confidently refer the prolonged first high stage of the lakes to the Nebraskan stage of far extended ice accumulations; the time when the lakes disappeared under a drier climate is represented by the Aftonian stage of wide recession of the ice-sheet; and the second rise of the lakes occurred probably during the time of culmination and final disappearance of the icefields. This second great division of the Glacial period included the maximum Kansan and Illinoian stages and the later Iowan and Wisconsin glaciation, being terminated when subsidence of the formerly high ice-covered land caused the continental glacier to be melted away, with the formation of very remarkable terminal and recessional moraines.

THE AFTONIAN INTERGLACIAL STAGE

The present writer, in a paper read at the International Geological Congress in Toronto in 1913,⁴ referred the interval between the high

⁴ Report of the Congress, published in 1914, pp. 455-466.

stages of Lakes Bonneville and Lahontan to the time of the Sangamon recession of the ice-border. Chains of lakes in Martin County, Minnesota, mark courses of interglacial rivers that flowed southward into the basin of the East Fork of the Des Moines, which were likewise regarded in that paper as of Sangamon age, being thought to afford proof of a great recession of the ice-sheet between the Illinoian and Iowan stages of glaciation, so far, probably, as to uncover the southern half of Minnesota.

More full consideration, however, of the relationship of the fluctuating western Quaternary lakes with the recognized diverse stages of growth and wane of the icefields, as here stated, has since led me to refer both the drying up of the western lakes and the erosion of interglacial river courses in southern Minnesota, with all the many occurrences of fossiliferous interglacial formations showing a very great interruption of the Ice Age on this continent, to the Aftonian stage of glacial recession. In comparison with that time of far withdrawal of the ice boundary, its Sangamon oscillation was of brief duration and relatively narrow areas.

Under this new review of the changeful and complex records of secular climatic conditions during the Ice Age, the Nebraskan and Aftonian stages appear very long; but the later stages, represented by drift sheets and interglacial beds that are far more extensively accessible to observation, forming the surface upon nearly all the glaciated area of this continent, are seen to have occupied less time than was before supposed. The most noteworthy revision of the sequence of changes in climate and oscillations of the ice-margin, as shown by the drift and associated interglacial beds, consists in the reference of the four glacial stages after the Aftonian interval to a practically continuous prevalence of widespread snowfall, bringing the ice-sheet to its maximum area and thickness, from which it waveringly receded, but was at last, in a geologic sense, rapidly melted away.

Short distances and duration of ice recession and return, or of fluctuation in adjacent or confluent icefields, one superseding or pushing back another, may sufficiently account for the observed Yarmouth, Sangamon, and Peorian land surfaces and fossiliferous beds that were covered by ensuing glaciation. Even the moraine-forming Wisconsin stage had changes of glacial currents on some areas during the final melting of the ice-sheet, which brought new outlines of its border and an overlapping of consecutive series of the marginal moraines.

In Iowa the fauna of the Aftonian deposits included the extinct mammoth and mastodon, an extinct horse, and species of the deer and rabbit yet living in this region. The flora comprised the pine and other conif-

erous trees, which were very abundant in northeastern Iowa, so that their wood is found in the sections of many wells, forming a broadly preserved forest bed. Leaves and wood of deciduous trees, as oak, elm, ash, walnut, and hickory, are also found, indicating a temperate climate similar to that of the present time.

Near Toronto, about 750 miles east-northeast from Afton, extensive interglacial beds contain remains of numerous species of mammals and trees identical with those of the Aftonian stage in Iowa and Nebraska, so that the Toronto formation is referred by Prof. A. P. Coleman to the same time. He also well refers more northern Canadian forest beds and lignite to Aftonian time, of which he writes as follows:

"Another widespread tract of interglacial deposits lies 350 or 400 miles north of Toronto, along river valleys of the James Bay region, with an extent from east to west of 100 miles and from north to south of 50. It includes 27 known outcrops of interglacial lignite or peat, scattered over an area of several thousand square miles. Logs of wood 17 inches in diameter have been found in the beds."⁵

In twelve counties of southern Minnesota, wells in the glacial drifts encounter interglacial beds containing wood, layers of peat, and occasionally shells of fresh-water and air-breathing mollusks, which layers are underlain and overlain by till, the direct deposit of an ice-sheet. These counties, described by the State geologist, the late Prof. N. H. Winchell, and by the present writer, in the first volume of the Final Report of the Geological and Natural History Survey of Minnesota, are, in their order from east to west, Fillmore, Mower, Freeborn, Steele, Faribault, Martin, Jackson, Cottonwood, Brown, Redwood, Lyon, and Rock counties.

Professor Winchell recorded many such wells in Mower County and adjacent parts of Fillmore County that penetrate a bed of peat carrying pieces of wood thought to be pine and cedar. This interglacial peat bed, varying from about one foot to six or eight feet in thickness, lies at 20 to 25 feet beneath the surface of Le Roy and Grand Meadow townships and the city of Austin. In other parts of Mower County it occurs at depths of 35, 45, and 50 feet. It probably is continuous with the extensive interglacial forest bed of Aftonian age in northeastern Iowa which was studied early and well reported by McGee. The other counties to the west have less abundant records of wells that pass through or into interglacial forest and peat beds, which would indicate that there they were largely removed by the erosion of the ensuing stages of glaciation.

Evidence of a long interglacial stage, here regarded as the Aftonian,

⁵ Report of the International Geological Congress in Toronto, 1913, pp. 435-449.

which interrupted the Ice Age in the southern half of Minnesota, is supplied by the exceptional chains of lakes before noted in Martin County, one of the central counties in the southernmost tier of this State. These chains of lakes are three in number and are named the East, Central, and West chains.

South Creek receives the outflow from the East chain, which extends in a somewhat irregular northerly course for 12 miles from the Iowa line. This chain comprises eight lakes, varying from a half mile to two miles in length, with from a half to two-thirds as great widths. These lakes are bordered by rolling areas of till. Their shores ascend 30 to 40 feet, mostly by quite steep slopes. The spaces between the lakes are, in some cases, marshy and as wide as the narrower parts of the lakes, but other adjoining lakes are connected by contracted channels, such as might be cut by the outflowing stream. Thus the series does not occupy depressions in any well marked and continuous valley.

About twenty lakes are included in the Central chain, extending 22 miles in an almost perfectly straight north to south course, from Perch Lake, three miles south of Watonwan County, to Iowa Lake, which is crossed by the State line. This series of lakes lies three to six miles west of the East chain. Its outlets are South, Center, Elm, and Perch creeks, all flowing eastward.

On both sides of the Central chain of lakes, as in the case of the East chain, the adjoining country consists of till, which rises to a moderately undulating expanse, 30 to 40 or 50 feet above the lakes. Though forming a very distinct, straight series, these lakes do not occupy a well defined valley, for its width varies from one mile or more to less than an eighth of a mile, and it is interrupted in three places by water-divides which are 10 to 15 feet above the adjoining lakes. Silver and Iowa lakes are the headwaters of South Creek, and have their outlet by a stream that runs nearly along the State line to the south end of the East chain. The middle part of the Central chain, reaching 12 miles from Summit Lake to the Twin Lakes, is tributary to Center Creek, and its portion farther north, excepting Perch Lake, is within the belt drained by Elm Creek.

The West chain of lakes is less distinctly connected than the East and Central chains, from which it also differs in having the longer axes of some of its lakes transverse to the course of the chain, and in having shorter series of lakes joined with it as branches. Tuttle's Lake, at the south end of the chain, lies on the State line about four miles west of Iowa Lake, the south end of the Central chain. Thence the West chain reaches 20 miles northwesterly, then nine miles northerly, and then north-

west and west eight miles to Mountain Lake, in Cottonwood County, its whole extent being 37 miles. Its successive portions from south to north are tributary to the East Fork of Des Moines River, to Center and Elm creeks, and to the South Fork of Watonwan River. This West chain has about 25 lakes, extending through a region of moderately undulating till, deposited by the ice-sheet, with no noteworthy areas nor unusually thick included layers of water-deposited gravel and sand, which, indeed, is true of all this county.

An explanation of these series of lakes, which appears most probable, is that they mark avenues of drainage and occupy portions of valleys that were excavated in the till during the Aftonian interglacial stage, after ice had long covered this region and had deposited the greater part of the drift, but before other glacial stages again enveloped this area beneath the ice-sheet, partially refilling these valleys and leaving along their courses the present chains of lakes. Detailed description has therefore seemed needful, that we may compare the great amount of early glacial erosion and drift transportation and deposition, which preceded the Aftonian stage, with the relatively small amount that can be attributed here to later glaciation.

Why a widespread and long amelioration of the cold climate melted back the ice-sheet in Aftonian time so far from the former Nebraskan border, with which the later Kansan and Illinoian border nearly coincided, it is hardly possible to conjecture, unless there was a subsidence of the continent during the later part of the Nebraskan stage, followed after the Aftonian stage by a second high continental uplift.

KANSAN GLACIATION

It is reliably proven that the Ice Age was much diversified and even very complex. Yet I believe it more reasonable to ascribe all our North American drift formations to one prolonged and continuous Glacial period, with great fluctuations of the ice-border, especially in the interior of the continent, than to regard our Ice Age as twofold or threefold, in the sense of having had its vast ice-sheet wholly melted away, or even nearly so, with ensuing renewal of snow and icefields.

Geologically very rare, an ice age would scarcely be duplicated with so nearly the same limits of ice extension upon half of our continent. The same general conclusion is also, as I think, applicable to the European glaciation. Almost inconceivable geologic duration divided the Permian and Pleistocene ice ages. In this most recent ice age, which continued to the threshold of the historic period, I can not think that the stupen-

dous climatic changes implied in the glaciation could permit complete repetition of the continental ice-sheets in America and Europe, and extend them in each case to so nearly the same maximum limits in the earlier and later parts of the Glacial period. It is better, until proofs are obtained more fully in the central regions of the drift areas on each continent, to regard their time of glaciation as one and continuous, with much areal oscillation, such as is proverbial of weather, during both the general stages of growth and departure.

All the ground that was relinquished by the ice-sheet during its Aftonian recession, which doubtless reached north to the southern part of the Red River valley, nearly to the head of the Mississippi, and to the vicinity of James Bay, became again deeply enveloped by the snowfall and ice-fields of the Kansan and Illinoian stages, spreading in the basin of the Missouri and Mississippi rivers somewhat farther than the previous Nebraskan limit. The Keewatin glacial outflow southward extended at the maximum of the Kansan stage to the lower part of the Kansas River, to the Missouri below Kansas City, and to the Mississippi on the northeast boundary of Missouri. In the States of Illinois, Indiana, and Ohio the Labradorian glaciation later attained its maximum of the Illinoian stage, depositing the outermost drift over the northern watershed of the Ohio River, and in the vicinity of Cincinnati it extended beyond this river into the edge of Kentucky.

Along the upper course of the Missouri the border of the Keewatin ice-field at its Kansan maximum limit crossed that river to the drift boundary in Nebraska, South and North Dakota, and eastern Montana. Farther west the Cordilleran outflow of both the Nebraskan and Kansan stages seems generally to have been surpassed by the Wisconsin stage, which is thought also to have produced the greatest extension of local glaciers upon the more southern Cordilleran ranges, to Colorado and California.

In the greater part of New York and New England, where interglacial formations are very scantily developed or absent, the icefield of Nebraskan time may have persisted through the Aftonian interval and forward during the Kansan and later glacial stages to the Champlain stage, in which the Glacial period ended. The maximum thickness and area of the ice-sheet east of the Hudson River was reached by the late Wisconsin moraine-forming stage.

Much drift that had been eroded and borne far from its sources during the very long Nebraskan glaciation, having afterward in Aftonian time rested from its travel, was again in part gathered up into the Kansan,

Illinoian, and later icefields, to be carried forward until deposited by the final melting and retreat of the ice-border. Only where rock formations of restricted area have peculiar characters by which their boulders can be identified with certainty as distinct from all similar boulders supplied by other formations and districts is it possible to affirm positively the distance of their transportation.

Big Stone and Otter Tail counties, of western Minnesota, have rare granite boulders with included fragments of hornblende schist,⁶ like much of the granite forming the Giants' or Mesabi range, which was probably their source. These boulders appear to have been carried about 200 miles southwest and west-southwest. Their glacial journey ran athwart the southeastward courses of the predominant Keewatin ice currents and outflow during the Kansan and later glaciation in that district, so that we must ascribe their transportation to the earlier Nebraskan stage. It was probably contemporaneous with the Patrician ice currents which spread from north of Lake Superior and carried their drift nearly or quite to the Ohio River, as before noted.

In Lucas County, of southern Iowa, a mass of drift copper weighing more than 30 pounds⁷ undoubtedly was borne by the currents of the ice-sheet about 600 miles, from the present copper mining region south of Lake Superior or from Isle Royale, first southwestward and later southward through eastern and southern Minnesota, passing west of the Wisconsin driftless area. Its journey probably was accomplished mostly during Nebraskan time.

The farthest recognized origin of rock fragments in the drift of our continental ice-sheet, recorded in part by Dr. Robert Bell, of the Canadian Geological Survey, whose observations are supplemented by the present writer, is from James Bay southwest to North Dakota and Minnesota. The rock is "dark grey, granular, siliceous felsite or greywacke, . . . characterized by round spots, from the size of a pea to that of a cricket ball or larger, of a lighter color than the rest of the rock, which weather out into pits of the same form." It occurs as the bedrock, according to Dr. Bell, on Long Island, off Cape Jones, on the east coast of Hudson Bay, where it is narrowed to form James Bay, having there a southwestward strike and probably continuing under the sea for some distance in that direction. He noted that the abundance of pebbles and boulders of this rock is the most remarkable feature of the drift on the

⁶ Geological Survey of Minnesota, Final Report, vol. i, 1884, p. 626; vol. ii, 1888, p. 551.

⁷ C. A. White: Geology of Iowa, 1870, vol. i, p. 96.

west coast of James Bay and along the Attawapishkat, Albany, and Kenogami rivers, and that its fragments were found by him as far west as to Lonely Lake and south to Lake Superior.⁸ Farther to the southwest and south I have observed fragments of it, usually measuring only a few inches, but in some instances a foot or more in diameter, occurring very rarely in the drift in the northeastern part of North Dakota, where the largest piece ever found by me was about 30 miles south of the international boundary and 50 miles west of the Red River, and at numerous localities in Minnesota, where it extends at least as far south as Steele County, 75 miles south of Saint Paul and 1,000 miles southwest of its outcrop north of James Bay.

The drift travel so known, like the instances before cited, is referable mainly to the Nebraskan glaciation and to a great Labradorian ice current, for the later Keewatin currents, during the Kansan and ensuing glacial stages, could not permit drift derived from Hudson and James bays to be borne so far to the west. Moreover, the far southward transportation into southeastern Minnesota covered too great a distance to be due to the Kansan and later glaciation, although it may partly be so explained. After Nebraskan travel to northwestern Minnesota, the Steele County boulder may have been carried southeast during Kansan time, taking then a course nearly at right angles with its earlier journey.

From a review of these notes of boulders carried far by glacial currents, it appears that during an early part of Nebraskan time the Patrician radial outflow reached west across northern Minnesota as well as south across Michigan and Ohio. Afterward, probably during the greater part of that very long stage, its directions of glacial flow respectively upon the Keewatin and Labradorian areas in these States were nearly like the currents of the later Kansan and Illinoian icefields.

Chains of lakes in southern Minnesota, described in preceding pages, show that the drift there was mostly deposited before a great recession of the ice-sheet which is referred to the Aftonian stage. Three localities farther north in this State supply definite measures of the moderate thickness of the drift referable in these places to the Kansan and later stages, agreeing with the evidence of these lakes.

At New Ulm, about 30 miles distant northward, the later drift sheet, overlying a sand and gravel deposit that is probably Aftonian, has a thickness of 16 to 18 feet. Rushseba township, in Chisago County, about 50 miles north of Saint Paul and Minneapolis, has a surface sheet of till 10

⁸ Geol. and Nat. Hist. Survey of Canada, Annual Report, new series, vol. ii, for 1886, p. 36G; compare Report of Progress for 1878-79, pp. 22, 23C.

to 20 feet deep lying similarly on interglacial beds which include a thin layer of peat with decaying fragments of wood next beneath the till. More distant northwestward, at Barnesville, in Clay County, on the southern part of the area of the Glacial Lake Agassiz, a well penetrated through 12 feet of till into quicksand "containing several branches and trunks of trees, thought to be tamarack, up to eight inches in diameter, which lie across the well, and which, together with the inflow of water, prevented further digging." This well is in the till area of the village of Barnesville and about 80 feet below the highest beach of Lake Agassiz, which passes from south to north about three miles east of this village.

In 1888, at the time of my survey of that region, I considered the occurrence of this interglacial bed within the area of the glacial lake as good evidence that the ice-sheet had been melted back at least far enough to give outflow into Hudson Bay from the Red River valley, thus draining off the forerunner of Lake Agassiz. Subsequent studies, however, lead me to hold now the different view that probably an interglacial lake here may have cut its southern outlet, at the site of Brown's Valley, to a lower level than the well at Barnesville; or that the attitude of the land was unlike what it is now, having then such an ascent from south to north that the Barnesville locality during the interglacial time was above the general surface of the region at Brown's Valley, into which the River Warren, outflowing from Lake Agassiz, cut its deep, continuous valley. So I now think that we have in the section of this well only evidence of an ice-retreat (that is, a departure of the outer part of the ice-sheet) northward a little more than halfway between the south and north boundaries of Minnesota.

On the extensive area of the three chains of lakes and at the more northern places where the thickness of drift above the old interglacial land surface is known, the Kansan, Iowan, and Wisconsin glaciation, to the end of the Ice Age, effected little or no erosion and made only scanty deposits of till beneath the ice-sheet. Each of the three recorded sections, in New Ulm, Rushseba, and Barnesville, appears to have received its upper till, lying on the interglacial beds, from the drift gathered up into the ice-sheet, borne along in its basal portion, and laid down when the ice in which it had been held was melted away. This englacial drift appears, therefore, to have been equivalent generally to a deposit 10 to 20 feet thick.

THE YARMOUTH INTERGLACIAL STAGE

During its maximum Kansan extension the east margin of the Kewatin icefield probably coincided nearly with the present course of the

Mississippi from the Wisconsin driftless area south to northeastern Missouri. An ensuing return of a more temperate climate melted the Keewatin ice far back previous to the culmination of the Illinoian glacial stage, when an eastern icefield advanced into southeastern Iowa, crossing the present valley of the Mississippi along a distance of over 100 miles and covering a tract in Iowa about 10 to 20 miles wide. Remnants of a black soil, peat, branches of trees, and bones of the rabbit and skunk, found there on the Kansan drift, overlain by the western border of the Illinoian drift, show that for a considerable time this tract had a land surface before it was again covered by ice. This time of glacial recession from the farthest eastern limit of the Kansan glaciation, followed by the most western advance of the Labradorian icefield in its Illinoian stage, is named by Leverett the Yarmouth interglacial stage, from Yarmouth, Iowa, about 20 miles northwest of Burlington. At that village interglacial beds 43 feet in thickness were penetrated by a well, with 30 feet of overlying Illinoian till and 33 feet of underlying Kansan till.

ILLINOIAN GLACIATION

Although the glacial drift has a width of about 300 miles between the driftless area and the boundary of glaciation in Missouri and southern Illinois, the Keewatin and Labradorian icefields were not confluent there. An ice-dammed lake would thus have been held on the large unglaciated area of southwestern Wisconsin and its smaller adjacent parts in Minnesota, Iowa, and Illinois, whether such confluence occurred during the Nebraskan stage or in Kansan and Illinoian time. The absence of lacustrine beaches and deltas testifies that the Mississippi flowed through the driftless area during all the Ice Age without being obstructed to form a lake.

By the Illinoian ice-advance into Iowa when it attained its greatest westward extent, the Mississippi was displaced and caused to flow temporarily outside the ice-border, crossing the lower courses of the Maquoketa, Wapsipinicon, Cedar, Iowa, and Skunk rivers. Along this part of the boundary of Illinoian glaciation its drift is amassed in a wide but low marginal ridge, 40 to 60 feet above the adjoining surface.

Stream erosion on the Kansan drift sheet has much exceeded its amount on the Illinoian drift, indicating, as estimated by Leverett, a greater interval between their times of deposition than from the latter to the present time. The difference in contour, however, may be partly due to an originally patchy condition and inequalities of the Kansan deposition for the outer region of attenuation of its icefield, in contrast

with the more uniform sheet of drift laid down later from a thicker Illinoian ice-border, which could form a low terminal moraine.

The Keewatin and Labradorian icefields are here regarded as very certainly attaining respectively their greatest southward and southwestward areas in one general stage of prevalent snowfall and ice accumulation, called west of the Mississippi the Kansan stage, and from this river eastward the Illinoian stage. After the melting of each of these icefields from large southern tracts of their maximum extension, the subsequent more northern drift formations of the mainly receding continental glacier, which yet at many times halted or readvanced, with much complexity of its outlines, drift sheets, and marginal moraines, have been referred to Iowan and Wisconsin stages of glaciation. To the last belongs far the greater part of the area of the ice-sheet, including nearly all its surface deposits in Canada; but underlying the Wisconsin drift are seen on many tracts deposits referable to the preceding glacial and interglacial stages.

Wherever the northern and central icefields may have remained unmelted from the earliest Nebraskan stage onward to the close of the Glacial period in the Champlain stage, only a single sheet of drift resulted, such being probably true for much of the interior of Canada and for parts of New York and New England.

THE SANGAMON INTERGLACIAL STAGE

An interval separating the times of formation of the Illinoian and Iowan drift, the latter being closely coincident with the chief loess deposition, is shown by an old soil and leached subsoil of the original Illinoian surface, and occasionally by scanty beds of peat, overlain by the loess. It was named by Leverett in 1897 the Sangamon interglacial stage, from the county and river of this name in Illinois where such evidence of it was first observed.

In a paper before cited, written in 1913, I referred the arid climate by which Lakes Bonneville and Lahontan were dried up, between their times of high water, to this Sangamon stage of interruption in the continental glaciation; but such correlation in the records of these lakes and the Glacial period seems instead to belong surely with the very widely extended Aftonian recession of the ice-sheet. My erroneous study embodied in that paper served as a stepping-stone to reach this conclusion, from which the general time relationships in the series of secular climatic changes during the Ice Age are, as I believe, rightly ascertained.

IOWAN GLACIATION AND LOESS DEPOSITION

During the closing part of Illinoian time and continuing into the Iowan stage, a gradual subsidence of the northern ice-laden half of this continent gave low gradients to the Mississippi and its tributaries. A temperate climate then returned upon the previously high and cold region adjoining the ice-border. Rains washed into the valleys much silt from erosion of the drift sheets and from the formerly englacial drift that became exposed on the surface of the melting and receding Iowan ice-fields. Deep and wide floodplains of this alluvial silt, similar to the loess of the Rhine in Germany, whence it is so named, were spread along the Missouri, Mississippi, and Ohio valleys. Its time of most abundant deposition is marked by its northern boundary in northeastern Iowa, found by McGee to coincide with the margin of the ice-sheet at a stage of glaciation which has been named the Iowan stage. Within the area that was then ice-covered are many boulders, remaining from the englacial and at last superglacial drift, its finer part having been carried away by the streams from the melting ice to be deposited as loess.

Winds sweeping across the valleys bore far over the uplands a large portion of this fine silt from its floodplains when the rivers were reduced in size, as they doubtless flowed in restricted channels for the greater part of each year. Thus the loess was spread as a general mantle, usually a few feet thick, upon nearly all the extensive area occupied by the Kansan and Illinoian drift.

THE PEORIAN INTERGLACIAL STAGE

After the principal deposition of loess and preceding the advance of a lobe of the Wisconsin icefields near Peoria, in Illinois, an interglacial surface of the loess there was exposed to weathering, which has caused the name Peorian to be given to that interval of some glacial recession and readvance. It was apparently of less duration or areal extent than the Yarmouth and Sangamon stages, though the lobation of the morainic border of the later drift in the Mississippi basin presents a very remarkable change from the more regular previous boundaries of the ice-sheet.

Loess continued to be plentifully deposited in northwestern Iowa until the time of formation of the outermost Altamont moraine, of Wisconsin age, which in 1880 I observed to be bordered on its west side along a distance of 75 miles, from Guthrie County northwestward to Storm Lake, by an expanse of loess as high as the crests of the morainic hills. The sheet of Wisconsin till east of the moraine is 50 to 75 feet lower than

the loess, showing that the icefield there was a barrier preventing the loess from being spread over the lower area.

Immediately after southern Illinois and Indiana were bared by the recession of the ice in late Illinoian and Sangamon time, the early loess there was being laid down, being contemporaneous in part with Illinoian till. It was more abundantly supplied during the Iowan glacial stage, and its later deposition was of the same age as the Altamont moraine.

WISCONSIN GLACIATION

The very diversified drift sheet of the latest grand division of the Ice Age was named in 1894 by Chamberlin for the State of Wisconsin, where in 1877 he mapped and described its interlobate Kettle moraine. In 1879 the present writer traced its terminal moraines on Long Island, Martha's Vineyard, Nantucket, and Cape Cod. During the next fifteen years, in the service of the Minnesota and United States Geological Surveys, I mapped the courses of twelve marginal moraines formed by the Wisconsin icefields at their maximum extension and at times of pause or readvance interrupting their general retreat in Minnesota, Iowa, and South and North Dakota.

The scanty eroding action of the glacial currents while depositing the relatively smooth expanses of the outer and earlier drift, during each of the preceding stages, was strongly contrasted with the vigor of erosion displayed by the planed and striated bedrocks of many districts inclosed by the later moraines. When the ice-sheet heaped these morainic ridges and hills, it had worn into its adjacent bed of rock or of the old drift deposits, accomplishing much erosion on extensive tracts covered by the later and uneven Wisconsin drift, which has plentiful lakes and lakelets, reaching northward from the outermost large and continuous moraine and comprising the far greater part of our drift-bearing area.

Drainage from the Wisconsin ice-border in its lobate course across the basin of the Mississippi was also more vigorous than when the loess was deposited. The land depression of that time had been succeeded by a moderate reelevation, giving to this interior region of the continent nearly its present height. Wide and deep channels in the loess flood plains were soon eroded by the rivers, which brought down and deposited much sand and gravel from the Wisconsin drift, their finer silt being then mostly borne far southward to the lower Mississippi or even to its delta.

But the more temperate climate which had been restored, probably by a great subsidence of the continent after the Kansan and Illinoian glaciation, bringing at first much ice-melting and loess deposition, con-

tinued and was the principal cause of the lobation of the Wisconsin ice fields, their changing, stronger, and faster currents and their frequent accumulation of marginal moraines. The edge of the ice was then melted more rapidly, on the average, than in any previous part of the Glacial period, so that it acquired generally a steeper gradient of the frontal slope, due to the predominantly marginal melting and to much snowfall upon the border for a width of many miles. Whenever the increased marginal currents carried the ice forward to its edge at a rate equalling or sometimes exceeding that of its melting there, the mainly receding boundary was held stationary or was even pushed forward during several or many years, permitting the englacial and superglacial drift to be amassed in conspicuous terminal and interlobate series of ridges, knolls, and hills.

During this moraine-forming stage the southern portion of the ice-sheet from Lake Erie to North Dakota consisted of vast lobes, one of which reached from central and western Minnesota south to central Iowa. This lobe in its early maximum extent ended near Des Moines, and its margin was marked by the Altamont moraine, the first and outermost in the series of twelve successive marginal moraines of this time which are found in Minnesota. When the second, or Gary, moraine was formed, it terminated on the south at Mineral Ridge, in Boone County, Iowa. At the time of the third, or Antelope, moraine it had farther retreated to Forest City and Pilot Mound.

The fourth, or Kiester, moraine was formed when the southern extremity of the ice-lobe had retreated across the south line of Minnesota and halted a few miles from it, in Freeborn and Fairbault counties of this State. The fifth, or Elysian, moraine, crossing southern Le Sueur County, marks the next halting place of the ice. At the time of formation of this moraine the south end of the lobe had been melted back 180 miles from its farthest extent, and its southwest side, which first rested on the Coteau des Prairies, had retired 30 to 50 miles to the east side of Big Stone Lake and the east part of Yellow Medicine County. In its next recession this ice-lobe was melted away from the whole of Le Sueur County, and its southeast extremity was withdrawn to Waconia, in Carver County, where it again halted, forming its sixth, or Waconia, moraine. The seventh, or Dovre, moraine marks a pause in the retreat when the southeast end of the lobe lay on Kandiyohi County. Probably nearly all of the south half of Minnesota was at that time divested of its ice mantle, but nearly all of the north half was yet ice-covered. The glacial boundary across the State had an approximately east to west

course not far from Little Falls, where primitive men made quartz implements before the upper Mississippi was wholly uncovered from glaciation.

By its next recessions the ice-border was withdrawn to the eighth, or Fergus Falls, moraine and the ninth, or Leaf Hills, moraine. These are merged together in the prominent accumulations of the Leaf Hills, which reach in a semicircle from Fergus Falls to the southeast, east, and northeast, a distance of 50 miles, marking the southern limits of this ice-lobe when it terminated nearly due west of Little Falls and halfway between the south and north borders of Minnesota. Conspicuous moranic hills a few miles east of Little Falls and others in the north part of Morrison County and along its west side seem to be correlated with the Fergus Falls moraine. Much of the modified drift of the Mississippi Valley at Little Falls was deposited when the ice-sheet terminated at these hills, 5 to 15 miles distant to the east, north, and west.

When the tenth, or Itasca, moraine and the eleventh, or Mesabi, moraine were amassed, crossing the lake region at the head of the Mississippi, probably the gravel and sand of the modified drift were entirely deposited north of Little Falls. The twelfth, or Vermilion, moraine, the most northern mapped in Minnesota, skirting the south side of Net, Pelican, and Vermilion lakes, consists of relatively small drift hills and ridges, with very abundant boulders. Thence to the central gathering grounds of the ice-sheet, west, south, and east of Hudson Bay, doubtless many other moraines were formed by its wavering but mainly receding borders, which await discovery when the glacial drift of those wooded and very scantily inhabited regions shall be fully explored.

Contemporaneously with the accumulation of the Dovre and later moraines, the Glacial Lake Agassiz was formed by the retreating Kewatin ice-barrier in the basin of the Red River and Lake Winnipeg, with outlet across the continental watershed and along the Minnesota and Mississippi rivers. The earliest and highest Herman beach, much uplifted above its original level, has now, on the west side of this very large glacial lake, a northward ascent of about 35 feet in the first 75 miles north from its mouth, at Lake Traverse, about 60 feet in the second 75 miles, and about 80 feet in the next 74 miles to the international boundary. Farther to the north, in Manitoba, the rate of ascent of the early beaches is increased to two feet or more per mile, whereas the latest and lowest beaches are nearly horizontal. The uplift is found

to have advanced like a wave from Minnesota and North Dakota northward through Manitoba and northeast to Hudson Bay, permanently elevating the country as now, mostly about 500 feet above the height which it held when first uncovered by the late Wisconsin glacial melting.

Soon after the ice-front receded, and while it yet continued to be the northern barrier of Lake Agassiz, the uplift along the whole extent of this ancient lake, more than 600 miles from south to north, was practically completed. The southern half of the lake area was first raised nearly to its present height; later its northern half was elevated, while the southern part received only slight increase of height; and last the basin of Hudson Bay, near the center of the glaciated area of North America, has been raised from its Champlain marine submergence of 300 to 500 feet. A part of this elevation on the shores of Hudson Bay was shown by Dr. Robert Bell to have been very recent, and it is even probably still in progress.

Nearly the same amount and a similar gradual advance of this Wisconsin uplift, with continuation through Champlain time, are attested likewise by the northward ascent of the beaches of a very complex series of glacial lakes held in the basins of the present Great Lakes tributary to the Saint Lawrence by the barrier of the receding Labradorian icefield.

THE CHAMPLAIN STAGE

Subsidence of the heavily ice-laden northern half of our continent from its great preglacial elevation brought during the Sangamon interglacial stage, and more remarkably at the ensuing Iowan stage of glaciation, low slopes and very gentle currents of the Mississippi and its tributaries, with restoration of a temperate climate at the ice-margin, permitting much loess to be deposited along these valleys. Warm summers, favorable to the accumulation of marginal moraines, continued during the Wisconsin glaciation, although evidence of freer drainage from the ice-front, with deposition of much water-borne sand and gravel, indicates that in the Mississippi basin the maximum subsidence had been followed by a slight reelevation.

Toward the close of the Ice Age and coincident with the existence of Lake Agassiz and the Laurentian glacial lakes, the moderate uplift of the glaciated region from its Sangamon and Iowan depression extended farther north, advancing in general as fast as the ice-borders receded, but apparently it is not yet entirely completed. Indeed, considerable parts of the drift-bearing areas of North America and Scandinavia are still

undergoing small and slow oscillatory movements, not having fully reached isostatic repose.

That the land northward from Boston was lower than now while the ice-sheet was being melted away is proved by the occurrence of fossil mollusks of far northern range, including *Yoldia (Leda) arctica* Gray, which is now found living only in the Arctic seas, preferring localities that receive muddy streams from glaciers and from the Greenland ice-sheet. This species is plentiful in the stratified clays resting on the till in the Saint Lawrence Valley and in New Brunswick and Maine, extending southward to Portsmouth, New Hampshire. But it is known that the land was elevated from this depression to about its present height before the sea here became warm and before the southern mollusks, which exist as colonies in the Gulf of Saint Lawrence, migrated thither, for these southern species are not included in the extensive lists of the fossil fauna found in the beds overlying the till.

In the Saint Lawrence Valley the marine deposits reach to the southern end of Lake Champlain, whence the beds and this stage ending the Ice Age are named, to Ogdensburg and Brockville, and at least to Pembroke and Allumette Island, in the Ottawa River, about 75 miles above the city of Ottawa. The isthmus of Chiegnecto, connecting Nova Scotia with New Brunswick, was submerged, and the sea extended 50 to 100 miles up the valleys of the chief rivers of Maine and New Brunswick. The uplift from the Champlain sealevel was 10 to 25 feet in the vicinity of Boston and northeastward to Cape Ann; about 150 feet near Portsmouth, New Hampshire; from 150 to about 300 feet along the coast of Maine and southern New Brunswick; about 40 feet on the northwestern shore of Nova Scotia, thence increasing westward to 200 feet in the Bay of Chaleurs, 375 feet in the Saint Lawrence Valley opposite the Saguenay, and about 560 feet at Montreal; 150 to 400 or 500 feet, increasing from south to north, along the basin of Lake Champlain; about 275 feet at Ogdensburg, and 450 feet near Ottawa. The differential elevation was practically completed, as we have seen from the boreal character of the Champlain marine molluscan fauna, shortly after the departure of the ice-sheet. With the areas of the glacial lakes in the interior of the continent, this coastal region gives testimony of a wavelike elevation of the formerly ice-burdened portion of the earth's crust, proportionate with the glacial melting and closely following the retreat of the ice from its boundaries of greatest extent inward to the areas on which its waning remnants lingered the latest.

From the Champlain submergence our Atlantic coast was raised some-

what higher than now, and its latest movement from New Jersey to southern Greenland has been a moderate depression. The vertical amount of this Postglacial elevation above the present height, and of the recent subsidence, on the coast of New Jersey, New England, and the eastern provinces of Canada, is known to have ranged from 10 feet to a maximum of at least 80 feet at the head of the Bay of Fundy, attested in many places by stumps of forests, rooted where they grew, and by peat beds now submerged by the sea. As in Scandinavia, the restoration of isostatic equilibrium is attended by minor oscillations, the conditions requisite for repose having been overpassed by the early reelevation of outer portions of each of these great glaciated areas. The end of the Ice Age was not long ago, geologically speaking, for equilibrium of the disturbed areas has not yet been completely attained.

ESTIMATED TIME RATIOS

In correlating our continental glaciation with the two stages of high water of Lake Bonneville, as noted by Gilbert, Nebraskan time appears to have far exceeded the combined Kansan, Illinoian, Iowan, and Wisconsin glacial stages, in a ratio of not less than five to one. The Aftonian stage, when the border of the ice-sheet melted over wide areas, but afterward advanced even beyond its previous extent, probably coincided with the long time when Lake Bonneville was reduced by evaporation to an area similar to the Great Salt Lake, or may indeed have been wholly dried up, that time of desiccation having been longer than the Postglacial period.

The latest Wisconsin stage, with the formation of its many recessional moraines, saw the ice-sheet gradually melted away. Since the retreat of its border from central Minnesota, the Mississippi River has eroded its gorge below the Falls of Saint Anthony, which Prof. N. H. Winchell, by comparing its recent rate of erosion with the length of the gorge, estimated to have required about eight thousand years. Similarly the Niagara Falls and gorge supply evidence, according to G. K. Gilbert, Prof. G. F. Wright, and the present writer, that the northward recession of the ice-border uncovered the region of Lakes Erie and Ontario about seven thousand years ago. These measures of late Glacial and Postglacial time in America accord well with recent surveys by Baron De Geer in Sweden, where the last twelve thousand years have witnessed the melting of the latest part of the European ice-sheet.

During the early part of the time represented by erosion of the Saint Anthony gorge, the later seven marginal moraines in the series of twelve

mapped in Minnesota were accumulated, marking pauses or slight readvances in the wavering general recession of the glacial boundary. The seventh to the twelfth of these moraines were formed contemporaneously with the Glacial Lake Agassiz, besides probably numerous others farther north, beyond the twelfth, or Vermilion, moraine. But the entire duration of Lake Agassiz, estimated from the ratio between the erosion and beach deposits of its shores and those of the Great Lakes tributary to the Saint Lawrence, can not comprise more than two thousand years, the ratio being certainly no greater than as one to four or five. Therefore it may be inferred that the Wisconsin stage of glaciation, from its earliest Altamont moraine to the end of the existence of Lake Agassiz, did not exceed four or five thousand years, having begun about ten thousand years ago. The principal uplift of the continent from its subsidence beneath the weight of the ice-sheet took place while Lake Agassiz yet existed, the Champlain submergence being thus mainly terminated at the same time with the melting of the latest remnants of the vast continental icefields.

Recurring to Gilbert's estimate of the ratio for the high stages of Lake Bonneville, we may refer the Kansan and later stages of the ice-sheet, with the Yarmouth, Sangamon, and Peorian recessions and readvances of the glacial boundary, to a relatively late part of the Ice Age, during the second high rise of that lake, measured probably by about 40,000 years and ending nearly 5,000 years ago. Under this view the maximum area of the Kansan icefield was perhaps attained, as thought by Leverett, twice as long ago as the farthest advance of the Illinoian icefield, which overlapped the edge of the Kansan drift. The successive farthest limits of the ice-border in these stages, noted approximately, may have been about 40,000, 20,000, 12,000, and 10,000 years ago, respectively, for the Kansan, Illinoian, Iowan, and Wisconsin glaciation.

The long Aftonian interval, bringing far retreat of the outer part of the ice-sheet, was probably about 50,000 years ago. Earlier the very prolonged Nebraskan glaciation, correlated with the first great rise of Lake Bonneville, appears to have extended through fully 150,000 years. Strict acceptance, however, of the ratio from the lacustrine record, as in the proportion of five to one, would give even 200,000 years, on this provisional time scale, for the formation of the Nebraskan drift sheet, accounting very amply for its observed thickness beneath the Aftonian beds and the later glacial drift in Iowa and southern Minnesota.

Within the first half or third of the Nebraskan stage very thick ice accumulation southwest of Hudson and James bays, upon the present area of Patricia, a district of Canada, caused currents of glaciation to

reach thence southward, over the basins of Lakes Huron and Michigan, nearly or quite to the Ohio River and westward across Minnesota. Through all the later and longer part of the Ice Age the Labradorian and Keewatin glacial currents passed transversely across those early courses of dispersion of Patrician drift.

LATE PLEISTOCENE HISTORY OF THE LOWER MOHAWK AND MIDDLE HUDSON REGION ¹

BY JAMES H. STOLLER

(Presented before the Society December 29, 1921)

CONTENTS

	Page
Introduction.....	515
Previous interpretations.....	516
New facts and rediscussion.....	517
General statement.....	517
Malta delta stage.....	519
Saratoga delta stage.....	519
Coveville delta stage.....	521
Origin of Saratoga Lake.....	521
Origin of Coveville Inlet.....	522
Development of the Round Lake-Anthony Kill Channel.....	523
Development of the Aqueduct-Cohoes gorge of the Mohawk... ..	524
Deduction bearing on the Pleistocene history of the Champlain-Hudson Valley.....	525

INTRODUCTION

Some additional data gathered in recent field-work seem to afford a clear explanation of the drainage history of this region, about certain features of which divergent views have previously been held, and also have a bearing on the more general problems of the Pleistocene history of the Hudson-Champlain Valley. The key to the drainage problems involved is found in the repeated shifting of the course of the Iroquois-Mohawk River as its flooded and sediment-bearing waters flowed across an area from which the static waters of the Mohawk-Hudson region (here referred to as Glacial Lake Albany) were receding. The origin and distribution of the sand-plains of the region, the origin of Saratoga Lake and of Round Lake, of the "old channel of the Hudson west of Schuyler-ville," and of the Coveville Inlet of the Hudson River are explained.

¹ Manuscript received by the Secretary of the Society February 3, 1922.

The features discussed are within the areas covered by the Schenectady, Saratoga, Cohoes, and Schuylerville topographic sheets.

PREVIOUS INTERPRETATIONS

Woodworth was the first to refer to (in connection with glacial history) the preglacial rock channel trending northeasterly from near Schenectady, named by him the Ballston Channel. He pointed out that the channel is dependent on structure, and that "erosion in Pleistocene times has excavated the channel along the vertical beds, which are evidently separated from the horizontal strata on the east wall of the valley by a fault." He made no reference to the origin of Ballston Lake, which occupies a portion of the bottom of the channel. In regard to Saratoga Lake and Round Lake, Woodworth² stated as a probability that they are "unfilled depressions marking the site of an old valley west of the present Hudson gorge."

The writer was the first to call attention to the topographic evidence that Ballston Channel afforded a passage for the flooded Mohawk, when blocked by the emerging delta deposits at Schenectady due to the subsidence of the Lake Albany waters, and to the clearly marked erosional features produced by the deflected currents.³ He suggested that Ballston Lake occupies a portion of the Ballston Channel which has been more deeply gouged out by ice erosion than elsewhere. In regard to Round Lake he considered that the broad basin, surrounded by slopes of Pleistocene clays and sands, at the bottom of which Round Lake lies, was caused by the erosive work of the flooded Mohawk waters at that stage in the subsidence of Lake Albany when the Mohawk currents were diverted from the Ballston Channel southeastward toward the Hudson Valley at Mechanicville.

In regard to the present course of the Mohawk, the writer considered that the gorge beginning at Aqueduct, three miles below Schenectady, and extending to Cohoes originated as due to erosion by overflow waters from the Ballston Channel at times when the Mohawk floods were at their maximum, and that the spillway thus established was gradually deepened into a gorge and the northward course of the Mohawk thus eventually undercut.

Fairchild reached the same conclusion as the writer in regard to the deflection of the Mohawk waters through the Ballston Channel, and from the Ballston Channel southeastwardly toward Mechanicville.⁴ He ex-

² J. B. Woodworth: N. Y. State Mus. Bull. No. 84, p. 75.

³ J. H. Stoller: N. Y. State Mus. Bull. No. 154, pp. 30-33.

⁴ H. L. Fairchild: N. Y. State Mus. Bull. Nos. 209, 210, p. 38.

plained Round Lake and Saratoga Lake as ice-block depressions. He states: "The simple and entirely sufficient explanation of Round Lake is that it occupies an ice-block kettle." And: "The basin of Saratoga Lake, like that of Round Lake, appears to be an ice-block depression." The diversion of the Mohawk River from its northward course to its present channel from Aqueduct to Cohoes Fairchild explained as the effect of land-tilting. He states:

"It is apparent that the Iromohawk in the northward flow had sufficient fall to have kept that path unless some outside force intervened. The differential northward uplift supplied the interference. The northward flow was weakened and discouraged and was diverted from the Ballston Lake channel into the present narrow channel eastward toward Cohoes."⁵

A physiographic feature evidently connected with drainage conditions in late glacial times is that of the cove at Coveville, on the west bank of the Hudson River. Woodworth explained this as connected with an old channel of the Hudson west of Schuylerville. Describing the present aspects of the channel as a "hanging valley," he states:

"The cove at Coveville, in its relation to this hanging valley, shows clearly that a large stream at one time flowed southward over the wall of the gorge at this place into the main gorge of the Hudson River, and was arrested after a slight amount of cutting had been accomplished. . . . The Hudson River must have at one time flowed through this Coveville Valley at a time when the bed of the river was in this latitude approximately 100 feet higher than it now is."⁶

NEW FACTS AND REDISCUSSION

GENERAL STATEMENT

Both Saratoga Lake and Round Lake occupy depressions in bedrock, as is shown by the occurrence of rock outcrops at the present margins of both lakes. The greatest depth of Saratoga Lake, as determined roughly by soundings, is 55 feet. This depth occurs just off Snake Hill, a mass of folded rock on the southeastward border of the lake. The present elevation of the lake is 204 feet, making the lowest portion of the bed of the lake 149 feet above sealevel. The greatest depth of Round Lake is 27 feet, the average of 12 soundings in different portions of the lake being 23 feet. The present elevation of the lake is 188 feet, and, deducting 27 feet, we have 161 feet as the lowest portion of the lake bottom. The Round Lake

⁵ H. L. Fairchild: N. Y. State Mus. Bull. No. 195, pp. 14, 15.

H. L. Fairchild: N. Y. State Mus. Bull. No. 195, p. 13.

⁶ J. B. Woodworth: N. Y. State Mus. Bull. No. 84, p. 196.

rock depression continues easterly along the broad valley, followed by Anthony Kill, to the Hudson Valley at Mechanicville.

Whether the rock depression in which Saratoga Lake lies is continuous with that of Round Lake can not be determined by surface inspection because of the mass of Pleistocene clays and sands (Lake Albany deposits) that occupies the three-mile interval between the two lakes.

Ballston Lake, as stated above, occupies a depression in the bottom of the Ballston rock channel. Its surface stands at 285 feet elevation, or about 15 feet below the general level of the floor of the rock channel.

The outstanding physiographic features, about which there is no question, are an old rock valley at 300 feet elevation (the Ballston Channel) and other rock depressions (perhaps forming a rock valley) a few miles eastward from the former and at a level more than 100 feet lower. These rock-rimmed depressions now lie at the bottom of broader depressions, the slopes of which consist of Pleistocene deposits, for the most part the clays and sands which were laid down in Lake Albany.

In mapping the Pleistocene deposits of the region, we find evidence of broad watercourses extending from the Ballston Channel to the depressions in which Saratoga Lake and Round Lake lie and beyond to the valley of the Hudson. In these watercourses the clay and sand deposits are largely swept away and worn rock surfaces are exposed; or where till occurs the finer materials have been largely removed, leaving an eroded surface often scattered with numerous boulders.

There are three such watercourses diverging from the Ballston Channel in the area about East Line, north of Ballston Lake. Of these, one extends northerly, following the line of the old channel, as far as east of Ballston Spa, where it broadens and turns eastward to Saratoga Lake. A second glacial watercourse extends northeasterly from the locality of East Line and joins the former course about the southern end of Saratoga Lake. The third extends southeasterly to the Round Lake depression.

In considering the development of these watercourses, it is to be borne in mind that the subsidence of the Lake Albany waters took place by degrees. When the lake was at its full development its waters stood at about 360 feet at Schenectady, as shown by the level of the great sand-plain, representing delta deposits, extending southeastward from Schenectady. As soon as the Iroquois-Mohawk currents were deflected into the Ballston Channel they discharged into the lake in the region south and east of Ballston, transferring the work of delta-building to that quarter of the lake. When the next stage of recession of the lake waters super-

vened, the currents forced their way through the new area of delta deposits, producing the watercourses above mentioned.

MALTA DELTA STAGE

The delta deposits marking the first stage of subsidence of Lake Albany are now represented by areas of sand, or of predominantly sandy composition, having the topographic forms of sand-plains or of terraces bordering the watercourses above referred to. The original delta was spread over the whole region of country (excepting those portions which stood above the level of the lake waters) east of Ballston Spa to beyond the southern end of Saratoga Lake and southeastward over the area surrounding the Round Lake depression. The plain on which the village of Malta is located was the central portion of the area of deposition, and the general delta, developed at this stage in the subsidence of the lake, may be named the Malta delta.

The elevation of these sand areas does not vary much from 360 feet. The fact that the Malta delta now has approximately the same elevation above sea as the Schenectady delta is undoubtedly explained by post-glacial northward uplift. As previously reported by the writer, there is evidence that this differential uplift has been about $2\frac{1}{2}$ feet to the mile in the Schenectady-Saratoga region.⁷ It may be considered, therefore, that the Malta delta originally stood at a level some 30 feet lower than now; in other words, that it was built into Lake Albany when that body of water had subsided about 30 feet from the level of its waters at the maximum stage of development of the lake.

With the lowering of the lake waters to a level below that of the general surface of the Malta delta, the Iroquois-Mohawk currents, as above stated, forced their way through the deposits, breaking into several distributaries, thus originating the watercourses above described and leaving the present areas of sand-plains as remnants of the original delta.

SARATOGA DELTA STAGE

With the close of the second stage of subsidence of the Lake Albany waters another period of delta-building began. The delta marking this interval of a fixed level of the lake waters is represented by the sand-plain on which the greater portion of the village of Saratoga Springs is built and which stretches west, south, east, and northeast from that locality. The general level of this plain is 320 feet. That it originally extended farther to the south is shown by the occurrence of an isolated

⁷ J. H. Stoller: N. Y. State Mus. Bull. No. 183, p. 38.

area of sand at the same elevation west of Saratoga Lake and separated from the Saratoga plain by a broad water-swept depression. In its original eastward extension the delta probably covered the area which now in-

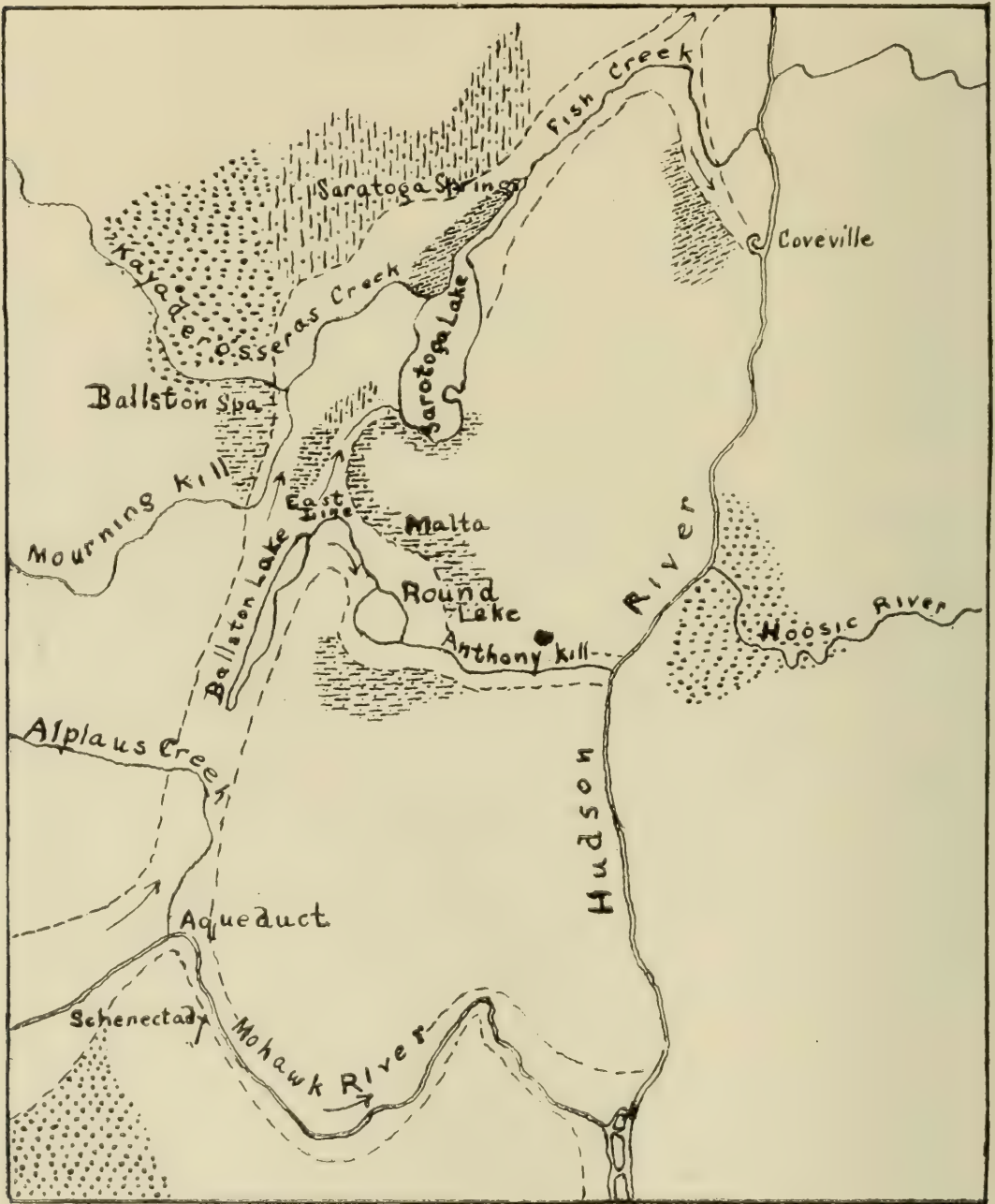


FIGURE 1.—Sketch Map of the lower Mohawk-middle Hudson Region

Showing the present drainage features and indicating the several courses of the Iroquois-Mohawk River in late Pleistocene times and the deltas formed. The deltas at Schenectady, north of Ballston Spa and at the mouth of Hoosic River were formed when Lake Albany was at its greatest development. The other deltas were formed at successive stages in the subsidence of the lake waters, as explained in the text.

cludes the northern portion of Saratoga Lake and the valley of Fish Creek for some miles northeastward from the lake.

Allowing for postglacial deformation, it may be deduced that the surface of the Saratoga delta was originally about 50 feet lower than the present plain. That is, it was built at a time when the Lake Albany waters had lowered to that extent, as compared with their highest level, when the Schenectady delta was formed.

With the further subsidence of the lake waters, a repetition of the previous steps of drainage development ensued. The Saratoga delta became land surface and the Iroquois-Mohawk currents cut their way through this emerging surface. The three divisions of the flooded river established at the time of the emergence of the Malta delta were maintained and their courses were extended through the added areas of land surrounding the shrinking lake. At the same time the currents broadened, their channels producing the broad water-swept depressions south and east of the Saratoga plain.

COVEVILLE DELTA STAGE

West of the northern end of Saratoga Lake and extending northeasterly west of Fish Creek is a sand-plain at 260-280 feet elevation. The plain is well defined, its margin being a bluff or steep slope, separating it from the lake and its outlet on the east (southeast) and from the eroded tract on the west. The extent is about $2\frac{1}{2}$ miles in length and an average of half a mile in width.

This sand-plain is interpreted as representing a third delta-building stage by the Iroquois-Mohawk, which began at the end of the stage of subsidence of the lake waters that caused the emergence of the Saratoga delta. This sand-plain may probably be correlated with the plain at the same general level developed west of Coveville, referred to below.

ORIGIN OF SARATOGA LAKE

We now come to an interesting phase in the drainage history of the Saratoga region. As soon as the subsidence of the Lake Albany waters had proceeded to the extent that the surface of the lake was lower than the rock bottom of the Ballston Channel, the gradients of the several distributing streams were increased. Their waters, escaping from the confines of the Ballston Channel, flowed toward the preglacial rock depression a few miles to the east. As the subsidence of the lake waters continued, progressively increasing the fall of the streams, the increased erosive power thus given to the currents enabled them to sweep away the

sands which filled those portions of the old rock depression where Saratoga Lake and Round Lake are now located.

The depression occupied by Saratoga Lake lies within the broad path of the two watercourses that extend northerly and northeasterly from the East Line district. The inference is that the present lake owes its origin to the erosive work of the Iroquois-Mohawk currents in sweeping away the Pleistocene deposits from the rock-floor now forming the bed of the lake. The difference of more than 100 feet in elevation between the rock bottom of the Ballston Channel and the rock-floor of Saratoga Lake was a determining condition in the origin of the Lake.

The present shore features of Saratoga Lake are in accord with this explanation of its origin. On the east shore is a rocky bluff with a mass of resistant rock (Snake Hill) jutting out into the lake. The rushing currents, in their northeastward course from the Ballston Channel, striking against the slopes of the rock hills east of the lake, formed this shore bluff by erosion. At a later stage in the development of the lake, when the mass of resistant rock stood out as a promontory, the currents were divided by it, and those deflected southward eroded the clay bluffs which stand back from the present margins of the lake at its southern end.

These currents which swept across the Saratoga Lake area moved northeastward and then eastward to discharge into the waters occupying the Hudson Valley. Erosion features along the valley of Fish Creek, the present outlet of Saratoga Lake, and at levels above the present valley bottom afford evidence of the work of broad and strong currents. The original features of this portion of the Iroquois-Mohawk Valley are, however, obscured on the north side of Fish Creek by sands that have drifted in in the recent period; but farther to the east and southward, from Grangerville to Coveville, erosion features due to stream-work are clearly shown, as observed by Woodworth.

ORIGIN OF COVEVILLE INLET

The water-swept area south of Grangerville is margined on its west side by undisturbed Pleistocene sands at approximately the 260-foot contour. The clearly defined sand terrace, two miles west of Coveville, trenched by a system of small streams of postglacial development, stands at 260 to 280 feet elevation. These areas of sands represent the Coveville delta stage in the subsidence of Lake Albany. The water-swept expanse at the 200-foot level, east of the terrace plain, extends to the recess in the rock wall of the Hudson Valley at Coveville.

The deduction to be drawn from these data is that it was the Iroquois-

Mohawk waters that formed the valley from Grangerville to Coveville which was regarded by Woodworth as an abandoned valley of the Hudson River. The recess at Coveville and the depression of the Coveville inlet were formed by the plunging waters of the glacial Mohawk as they fell over the rock wall of the Hudson gorge.

In Woodworth's interpretation the "old hanging channel" had its northern connection with the valley of the Hudson at Northumberland. To the writer it seems that the depression at 220-240-foot elevation, extending northeasterly from Grangerville to Northumberland, was for a time occupied by Iroquois-Mohawk currents, which found an exit to the Hudson Valley in that course. The depression is now till-covered and the hills, rising on either side to the 300-foot level, are also till-covered. It appears that the glacial Mohawk waters, at that stage in the subsidence of Lake Albany when the Coveville delta had emerged as land surface, may have spread over this depression and established a course to the Hudson Valley at Northumberland, thus lowering the surface of the till and producing the present channel features. At the same time a portion of the waters forced an outlet toward Coveville, and that channel was eventually reduced by erosion to an extent that the northward channel was undercut. The present broad depression extending southeasterly to Coveville was then developed as the bed of the Iroquois-Mohawk.

In postglacial times the course of Fish Creek has been shifted from that portion of its former channel which extended southwest from Victory Mills toward Coveville to its present channel, past Victory Mills to its outlet in the Hudson at Schuylerville. This portion of Fish Creek is clearly postglacial in origin, as is evidenced by the fact that it occupies a rock gorge and by the fall of about 100 feet from south of Victory Mills to its mouth, a distance of about $1\frac{1}{2}$ miles. It seems probable that this change of course of Fish Creek is a case of stream piracy. A small stream that flowed down the slope past Victory Mills, through headward cutting, tapped and diverted to its course the Fish Creek currents at the place in its bed where the sharp bend occurs, southwest of Victory Mills.

DEVELOPMENT OF THE ROUND LAKE-ANTHONY KILL CHANNEL

The Iroquois-Mohawk waters continued to course through the Saratoga Lake-Fish Creek Channel until such time as a lower outlet to the Hudson Valley by way of the Round Lake-Anthony Kill Channel of sufficient capacity to contain the entire volume of the Mohawk waters was established. That the Mohawk waters flowed through the latter channel there is convincing evidence. The valley which extends from the floor of

Ballston Channel at East Line southeastward to Round Lake presents all the features of a valley of erosion of recent origin made by broad and strong currents. At its upper end the valley is wide and open in its outer portion, while the middle portion forms a rock gorge with shelving walls about one-eighth of a mile in width. The gorge continues to Round Lake, widening in its lower part where its walls recede into well defined rock terraces. There is a fall of 112 feet from the floor of the Ballston Channel, taken at 300 feet at East Line, to Round Lake—a distance of $2\frac{1}{2}$ miles. The broadened lower end of the rock-cut valley opens into the general depression at the bottom of which Round Lake lies. The floor of this depression consists largely of till, with scattered boulders, and its slopes show terrace features, indicating the erosive work of sweeping currents. The depression continues as a broad and deep valley of erosion, opening into the Hudson Valley at Mechanicville.

The factors which determined the diversion of the Mohawk waters to the Round Lake Channel, terminating the Coveville outlet stage of the drainage history of the region, were as follows: When the East Line distributaries were developed, the one flowing southeasterly at first pursued a sluggish and meandering course across the Pleistocene deposits lying over the Round Lake region. Eventually and *pari passu* with the subsidence of the lake waters, through lateral and downward cutting, the present Round Lake basin was gradually developed. The escaping waters from the Ballston Channel now falling over the rim of the old rock depression, some 100 feet lower than the rock-floor of the channel, eroded a gorge which eventually, through deepening and recession, undercut the main valley. As soon as this side valley had been enlarged through erosion to the capacity of containing the volume of waters flowing in the main valley the river was diverted into the new course.

DEVELOPMENT OF THE AQUEDUCT-COHOES GORGE OF THE MOHAWK

A similar explanation applies to the postglacial gorge of the Mohawk from Aqueduct southeasterly to Cohoes. The nearly vertical wall of the gorge on the north side of the river at Aqueduct is marked at its summit by the 340-foot contour. Back of the summit there is a marginal eroded area rising to the 360-foot level or somewhat higher. South of the gorge the wall of the valley is of equal height. When the Iroquois-Mohawk waters were first diverted into the Ballston Channel a place of overflow of the waters over the margin of the channel at Aqueduct was developed. This may have been due to the wall at this place having been slightly

below 360 feet in elevation or it may have resulted from recurring high-water stages of the Mohawk waters. An overflow, once started, or, if taking place recurrently at times of flooded waters, gradually through erosion lowered the wall of the valley so that a permanent lateral outlet stream was eventually established. The overflow waters from the Iroquois-Mohawk were engaged a longer time in cutting the Aqueduct gorge than that at East Line because of the greater length of the former. The fall or rapids of the overflow stream was first at Vischers Ferry, and it was not until this fall had receded to Aqueduct, a distance of 5 miles, that the full volume of the Mohawk waters was diverted to its present channel.

The explanation given by Fairchild of the origin of the Mohawk gorge from Aqueduct eastward, namely, that it was due to a reversal in direction of the Iroquois-Mohawk currents in the Ballston Channel consequent upon northward uplift of the region, while consonant with the steps of glacial drainage history, as above set forth, seems to the writer improbable, as being out of accord with physical principles. It would seem that regional uplift, taking into account the time element, would have increased the erosional work of the stream, thus enabling it to deepen its bed and to maintain its course, rather than have caused a reversal in the direction of flow of its flooded waters.

DEDUCTION BEARING ON THE PLEISTOCENE HISTORY OF THE CHAMPLAIN-HUDSON VALLEY

The erosional history of the lower Mohawk-middle Hudson region, as above interpreted, is incompatible with the view that sealevel waters occupied the Champlain-Hudson Valley in late Pleistocene times. The waters which covered the region following the retreat of the ice-front, whether forming a glacial lake or an estuary entering the Hudson Valley at New York, had withdrawn from this territory while yet the outlet of the great interior lakes was through the Mohawk Valley. The Saint Lawrence Valley was still filled with ice and the front of the ice-sheet stood across the Champlain-Hudson Valley somewhere north of the area described in this paper. When the ice-front had so far retreated to the north as to open a lower outlet along the northward slope of the Adirondacks, thus ending the Iroquois-Mohawk stage of drainage, the new outlet may have followed the Champlain-Hudson Valley to the ocean at New York. But these waters, as they coursed through the middle Hudson region, were certainly fluvial, covering only the present valley bottom of the Hud-

son, inasmuch as the erosional features of the region produced during the Iroquois-Mohawk stage have remained unchanged.

The conclusion is that at no time was there a continuous body of marine waters connecting the Saint Lawrence arm of the sea with the ocean at New York.

KENNECOTT GLACIER OF ALASKA¹

BY ALAN M. BATEMAN

(Read before the Society December 29, 1920)

CONTENTS

	Page
Introduction.....	527
Topographic setting.....	528
Climatic setting.....	529
Description of glacier.....	530
Type.....	530
Location.....	531
Dimensions.....	532
Surface.....	532
Edges.....	534
Overriding.....	535
Melting and discharge.....	536
Movement of the glacier.....	537
Method of obtaining data.....	537
Results.....	538
Discussion of results.....	538

INTRODUCTION

A few observations and measurements of Kennecott² Glacier were made by the writer,³ incidental to other geological work in Alaska. The data are here presented as "scientific by-products." The field observations were necessarily disconnected, but no apology is offered for the sketchiness of this paper, for the data may possibly be of use to others.

The Kennecott Glacier is situated in Alaska, on the south slope of the Wrangell Mountains. The town of Kennecott is near the foot of the glacier, some 200 miles from the coast by the route of the Copper

¹ Manuscript received by the Secretary of the Society May 11, 1921.

² The U. S. Geological Survey orthography correctly gives the spelling of this name as "Kennicott," but the post-office, town, and mining company name are spelled as "Kennecott." As the latter is common usage throughout the country, it is followed in this paper.

³ Extending over the field seasons of 1915 to 1920.

River and Northwestern Railroad. (See figure 1.) It is reached from the railroad terminal and port of Cordova, which lies on the east side of Prince William Sound.

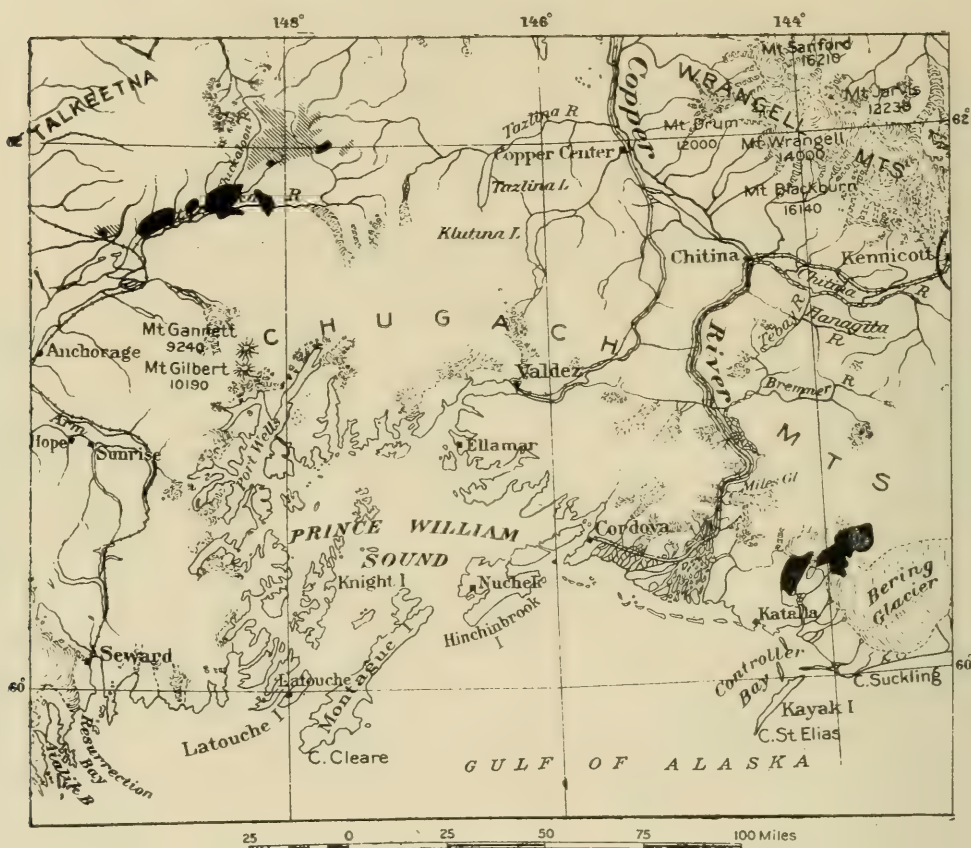


FIGURE 1.—Index Map of Part of Alaska

Showing location of Wrangell Mountains and Kennecott Glacier (after U. S. Geological Survey)

TOPOGRAPHIC SETTING

The gathering grounds of Kennecott Glacier are in the lofty Wrangell Mountains. These form an irregular mountain group, with a north-westerly-southeasterly trend, and have been and still are the seat of intense glaciation. They support extensive snowfields and innumerable large and small valley glaciers. The range lies north of the Gulf of Alaska and is separated from it by the high, rugged, snow-covered Chugach Range, and is thus an interior range of mountains. The higher peaks of the Wrangell Mountains rise to 16,140 feet and many are over 12,000 feet.

Kennecott Glacier emanates from Mount Blackburn, which rises to an elevation of 16,140 feet, and its largest tributary extends from

Regal Mountain, another lofty peak of the Wrangell Mountains. The glacier flows down Kennecott Valley (figure 2) the sides of which rise steeply to over 6,000 feet above the top of the glacier. The glacier is a



FIGURE 2.—*Kennecott Glacier, showing Moraines; Mount Blackburn in Distance*

remnant of a greater ice-tongue whose surface at the time of maximum glaciation, stood at a level about 3,000 feet higher than the present terminus.⁴ The latitude at this point is $61^{\circ} 30'$ north.

CLIMATIC SETTING

The coastal region of this section of Alaska is characterized by exceptionally heavy precipitation and much overcast weather. The summer temperatures are moderate and in winter the thermometer rarely reaches 0° Fahrenheit. Snowfall is abundant and the mountains near the coast contain extensive snowfields and are the seat of the greatest glacier development in Alaska. They are the gathering grounds for the great Malaspina and Bering River piedmont glaciers, in addition to numerous valley glaciers.

Inland from the mountains that border the coast the climate is different. The prevailing winds from the ocean lose much of their moisture in crossing the coastal mountains; the precipitation is lighter; the summers are short, sunshiny, and warm; the winters are long and cold and temperatures down to 65° below zero are not uncommon. Glaciers are abundant and of the valley type.

Unfortunately, climatological records for Kennecott are incomplete. From 1910 to 1920 there are only two years during which complete monthly temperatures are recorded and one year of complete monthly

⁴ See Plate III accompanying U. S. Geol. Survey Bull. 448, 1911, by F. H. Moffitt and S. R. Capps.

precipitation. These data at the town of Kennecott (elevation, 2,003 feet), are:⁵

Mean Temperature

1917	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1917	7.6	12.6	21.8	28.4	42.3	51.8	51.4	52.8	46.0	28.3	6.4	21.4	27.3
1918	5.2	6.0	9.4	28.2	40.0	51.4	56.8	51.0	47.8	30.9	19.2	9.5	29.6

Precipitation (Inches)

1919	1.03	0.15	0.18	tr.	1.44	tr.	2.30	0.20	2.00	1.07	1.04	1.55	10.96
------	------	------	------	-----	------	-----	------	------	------	------	------	------	-------

The elevation above sealevel of the recording station is approximately the same as the top of the glacier near this point. Some climatological records have been kept at the mines, about 4,000 feet above the town of Kennecott, but are too scattered to be of value.

This is the climatic setting of Kennecott Glacier, in the Wrangell Mountains.

Still farther inland beyond the Wrangell Mountains the precipitation becomes less and equals that of the semiarid and arid regions of southwestern United States. An annual precipitation as low as 7.76 inches has been recorded at Fairbanks.⁶ The summers are short and warm and the winters extremely cold. Glaciers do not exist and the region never has been glaciated, except for local small ice-tongues.

In comparing various Alaskan glaciers, particularly with respect to their rate of movement, this climatic difference must be taken into consideration. Differences of precipitation and temperature, and relative durations of summer and winter seasons would be expected to affect the rate of movement of glaciers. In comparing Alaskan glaciers with those of other regions, such as the Alps, other climatic factors also enter. Kennecott Glacier is situated in a latitude where sunlight in early summer persists for more than twenty hours of the day; but the sun's rays are more slanting and consequently less warm. The summer season is shorter and the mean annual temperature much lower; the duration of time when the air temperature is above 32° Fahrenheit is, therefore, much less.

DESCRIPTION OF GLACIER

TYPE

Kennecott Glacier is of the valley type (see figure 3). Two large branches, an eastern one, from Mount Regal, and a western one, from Mount Blackburn, coalesce about 6 miles above its terminal and con-

⁶ U. S. Geol. Survey Bull. 525, 1913, p. 27.

⁵ Records supplied by U. S. Weather Bureau.

stitute the main glacier. The Blackburn branch is fed by numerous large tributaries, all of which contribute their lateral moraines to form the medial moraines of the master glacier, imparting to it a pronouncedly ribboned appearance.

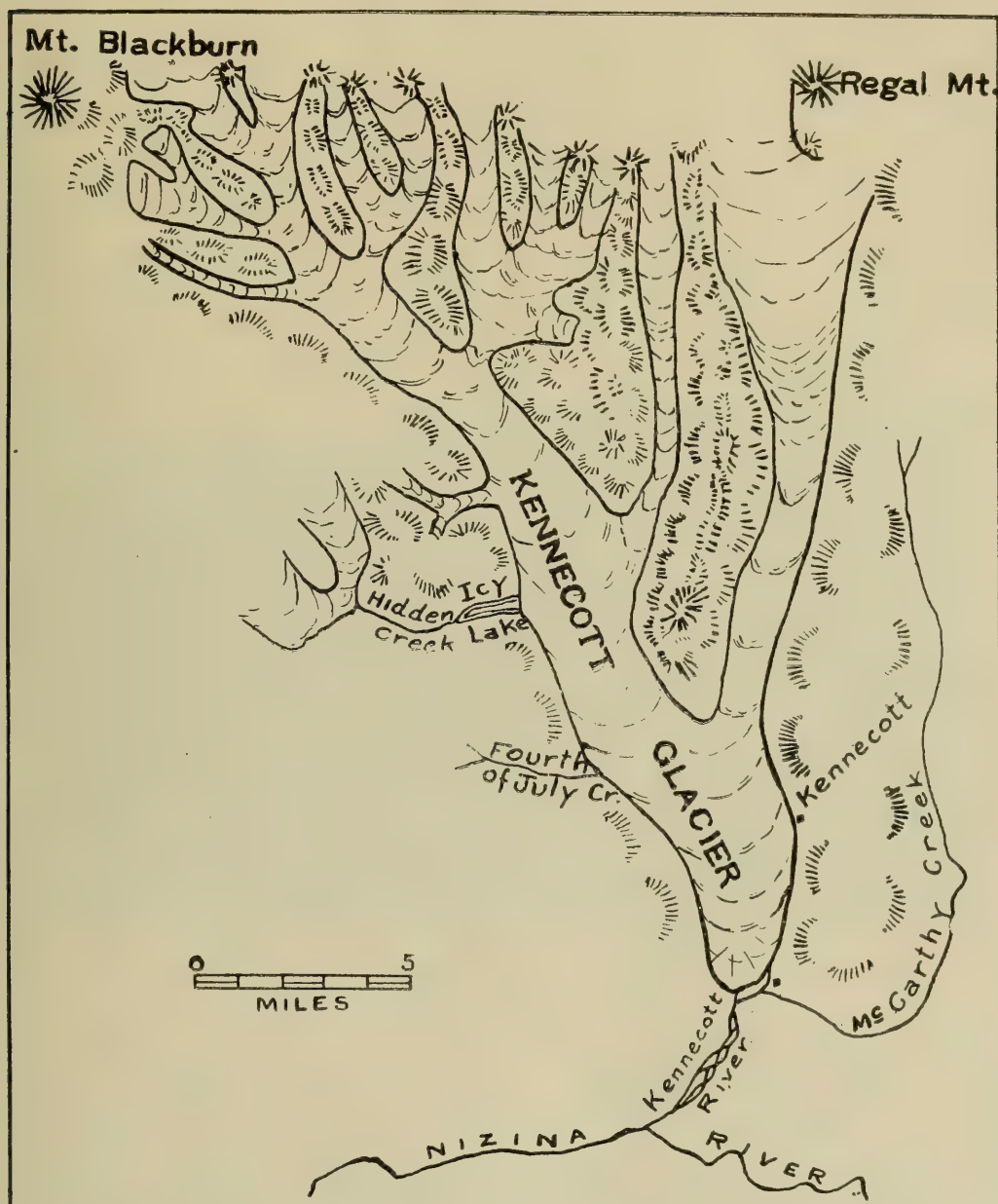


FIGURE 3.—Map of Kennecott Glacier, its Tributaries and gathering Grounds

Drawn from map accompanying Bulletin 374, U. S. Geological Survey.

LOCATION

The gathering grounds lie on the southern and eastern flanks of Mount Blackburn, on the southern slopes of Mount Regal, and along

the 25 miles of high divide connecting these mountains (figure 3). The adjacent gathering grounds on the northern slope of the Wrangell range supply the great Nabesna Glacier and its numerous tributaries. Kennecott Glacier thus emanates from a high and extensive névé field which is the mother of a number of large glaciers.

DIMENSIONS

The glacier proper starts high up on the flanks of Mount Blackburn (16,140 feet), at an elevation of about 13,000 feet, and descends to an elevation of 1,380 feet at its terminal. The total drop is thus about 11,600 feet, most of which occurs in the upper reaches. The lower part has a relatively gentle gradient, rising from an altitude of 1,380 feet at the terminal to about 4,000 feet, 15 miles upstream, or approximately 175 feet to the mile. The gradient steepens at this point, and the remaining difference in elevation, about 9,000 feet, occurs in about 10 miles. Part of this steep descent is marked by many prominent ice falls, which, from an inspection by the eye, appear to extend over a vertical range of about 5,000 feet. The total length of the glacier is thus about 22 miles. Its maximum width below the junction with the Regal branch is about 4 miles; above and below this point it is about 2 miles wide⁷ (figure 3). The whole glacier may be seen from certain vantage points on the surrounding peaks.

SURFACE

Viewed from a distance, the most striking feature of the glacier is its ribboned character, due to the distribution of white ice and debris (figure 2). For a mile or so up from the terminal, all of the glacier is of a somber color, due to distributed debris of the terminal moraine. Then white ice appears in the center, with bands of lateral moraine, approximately a half mile in width, at the sides. Still farther up, the irregularly distributed debris differentiates into two lateral moraines and seven medial moraines. These are narrow bands separated by white ice and extend upward with sinuous courses, becoming fewer and fewer in number until they give way to white ice at the ice falls. The lateral moraines persist as diminishing ribbons of debris well up toward the gathering grounds. Smaller transverse bands of debris, bowlike in plan, impart to the glacier the appearance of flowing and recall the conventional lines used to designate glaciers on maps. The distant view also

⁷ The elevations and distances here given are only approximate, based on rough triangulation and checked by U. S. Geol. Survey top. map accompanying Bulletin 374.

discloses a furrowed character, due to the numerous crevasses on its surface.

Closer inspection reveals a pronouncedly hummocky appearance, with broad depressions surrounded by steep ridges, above which rise many conical or irregularly shaped peaks (figure 4). Again, broad domes may characterize the surface. Some of these surface irregularities have a difference in elevation of as much as one hundred feet. White ice alternates with deep opaline blue ice and with dark patches of debris. Rivulets of water traverse the surface; some reach the margins of the glacier, others disappear in cascades down pipelike holes or in deep

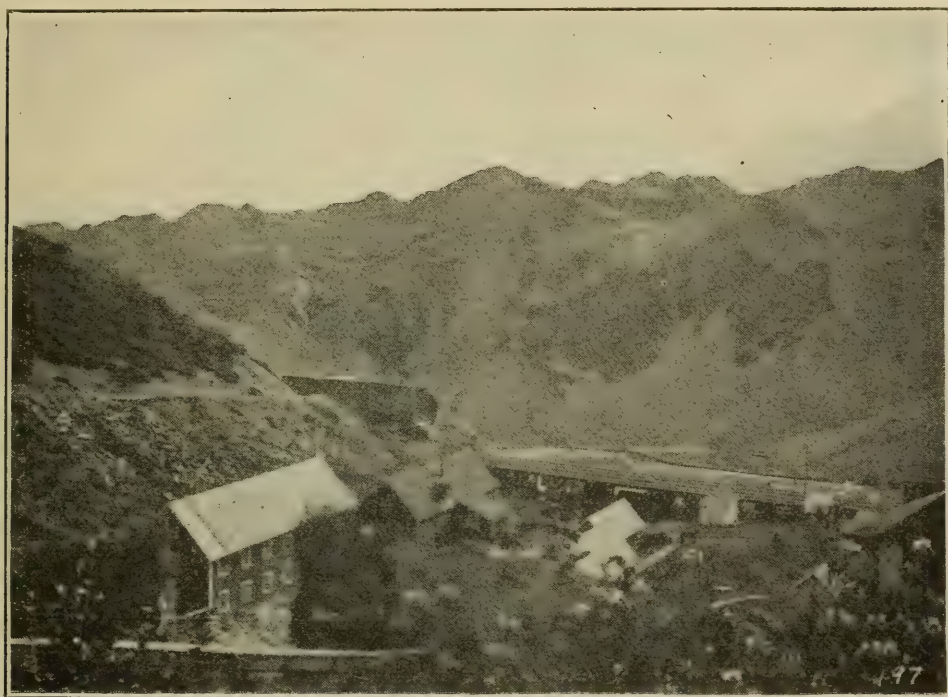


FIGURE 4.—View of Edge of Glacier opposite Kennerott

Gray is debris; black is melting ice.

crevasses. Underneath is a continuous dull gurgle or roar of running water, somewhat more noticeable near openings. The furrows which mark the crevasses are found to be deep, elongated depressions formed by the more rapid melting of the sides of the crevasses. Steep, elongated ridges of ice separate them, and the relief is from 10 to 100 feet; so that travel across them is in most places impossible.

Both central and marginal crevasses were noted. The lower six miles are relatively free from crevasses, but above this point, where the width of the glacier is less, crevasses are the rule rather than the exception. Crevasses are most abundant, of course, where changes in direc-

tion or grade occur. Where the grade steepens, marginal crevasses are prevalent and appear to extend across about one-quarter the width of the glacier. Some fourteen measurements of direction made on these marginal crevasses show that they point upstream and form an angle of 50 degrees with the edge of the glacier. This figure is a mean of all the measurements, but individual readings did not vary more than six degrees from the mean.

EDGES

The edges of the glacier are marked by numerous embayments and projections. The embayments appear to be formed by more rapid melt-

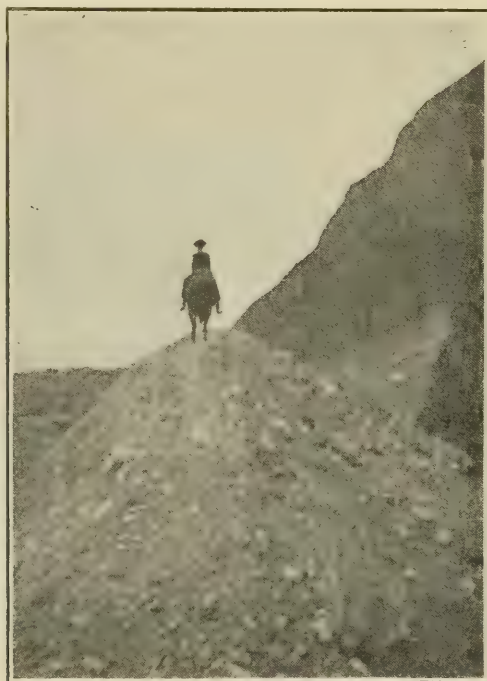


FIGURE 5.—Narrow A-shaped Moraine parallel to Edge of Glacier and higher than Top of Glacier

ing at certain places. They are usually half-moon shaped and may reach three hundred yards in diameter. The smaller ones are often filled by ponds of dirty glacier water. Small streamlets wind in and out along the edges, but their length is not great, for they all disappear, sooner or later, down into the glacier.

Till is present everywhere along the edges (figure 4). In some places it occurs in irregularly outlined hummocks or sporadic bunches or mantles; in others it is in the form of long moraines, A-shaped in cross-section, resembling eskers in shape, and parallel to the edge of the glacier (figure 5). These moraines are conspicuous topographic fea-

tures. They form almost straight lines, and individual ones may be four miles in length. They rise symmetrically to a height of more than 50 feet, with tops barely wide enough to support a footpath. The steep slopes are determined by the angle of repose of the gravel and boulders composing them. The base of the landward slope usually rests on the solid rock or talus slopes of the valley wall, while the glacier slope rests on ice or on other glacial debris, a hundred yards or so from the ice. Their tops are in many places several feet above the level of the glacier, so that a longitudinal valley separates them from the ice. The origin of these long, symmetrical, A-shaped moraines at first seemed puzzling; later they were observed in the making. At a high, steep-sloping edge of the glacier, debris was sliding down from the melting top. Accumulation had proceeded until it spread along the base of the glacier and lapped up on its side, like a talus slope at the base of a cliff, for a height of about 45 feet. The continuation of this process would result in a flanking mantle of debris parallel to the edge of the glacier and lapping well up on the side of the ice. Eventually, as melting of the side of the glacier continued, the ice would recede from the glacial talus slope, which then would fall over toward the glacier side and rest at the angle of repose, forming a symmetrical A-shaped moraine separated from the glacier. Further melting of the top of the glacier would result in the top of the moraine standing above the level of the top of the ice.

OVERRIDING

On the west side of Kennecott Glacier is a large embayment into the ice, which obviously at one time was occupied by a pond into which mud-laden water was discharged. Later the pond was drained. At the time of observation the material within the embayment was distinctly stratified with unsorted, coarse material at the bottom, overlain by about four inches of fine gravel, and with about two feet of stratified glacial silt on top. Subsequent movement of the glacier from north to south brought the north wall of the embayment over a part of the stratified silt, and when observed by the writer large boulders and till were sliding from the melting wall of ice down on top of the stratified silt. The boulders and till had accumulated to an average thickness of about five feet over an acre of the stratified silt, thereby producing a local unconformity. In a tunnel, driven for the purpose of drainage, through the ice of a projecting lobe separating two such embayments, at Kennecott, a similar condition was observed. In several other embayments, at present occupied by ponds of thick muddy water, the

deposition of silt is now taking place and is unquestionably forming stratified layers.

The stratified silt, overlain by boulders and till, was shown to the satisfaction of the writer to have been brought about under present glacial conditions clearly in the one glacial period, and in all probability within a few years. Such an occurrence, if remote from the present glacier, might hastily be interpreted as representing a glacial recession and advance or else a second glacial period.

MELTING AND DISCHARGE

Melting proceeds over all parts of the glacier, but is most rapid along the edges. No exact data are available as to the wastage on the top, though it appears to be little more than the annual accretion. Guide stakes stuck in shallow cracks to a depth of a foot were observed to stand up over the summer seasons.

All of the discharge takes place from the front of the glacier; no continuous marginal streams exist. Probably 75 per cent of the discharge emanates from the "pot-hole." This is a circular hole immediately in front of the glacier, which emits a column of water that is the source of Kennecott River. The depth of the hole is unknown. Usually the column of water rises a few feet above the level of the surrounding ground, but at times a giant column of water spouts up to a height of 15 to 20 feet. This "playing" of the "pot-hole" is interestingly coincident with the disappearance of Icy Lake, some 11 miles up the glacier (see figure 3). This lake lies on the west side of the glacier, where the wall of ice forms a dam directly across the right-angled tributary valley of Hidden Creek. The water of the creek impounds against the ice-dam and forms a lake, one-half mile wide and one and one-half miles long, the surface of which is covered by innumerable icebergs. Every autumn, and often in the spring, the lake suddenly disappears, and repeated observations show that almost simultaneously the pot-hole begins to "play." This establishes a direct subglacial connection between the lake and the pot-hole for a distance of 11 miles. The connection is also capable of transmitting a part of the pressure under which the water rises.

The volume of water in this subglacial stream is large. It also carries an abundance of glacial sand and gravel and is thus highly competent to produce corrasion. An interesting question arises as to whether such streams may produce an appreciable subglacial incision of the valley floor, and also if in large glacial valleys some of the cutting attributed to post-glacial processes may not have been formed in part during the later glacial stages of such subglacial streams.

MOVEMENT OF THE GLACIER

METHOD OF ATTAINING DATA

For the purpose of obtaining data relating to the movement of the Kennecott Glacier, a number of stakes containing flags were set firmly in the ice (see figure 6). The stakes were not placed in line, owing to the

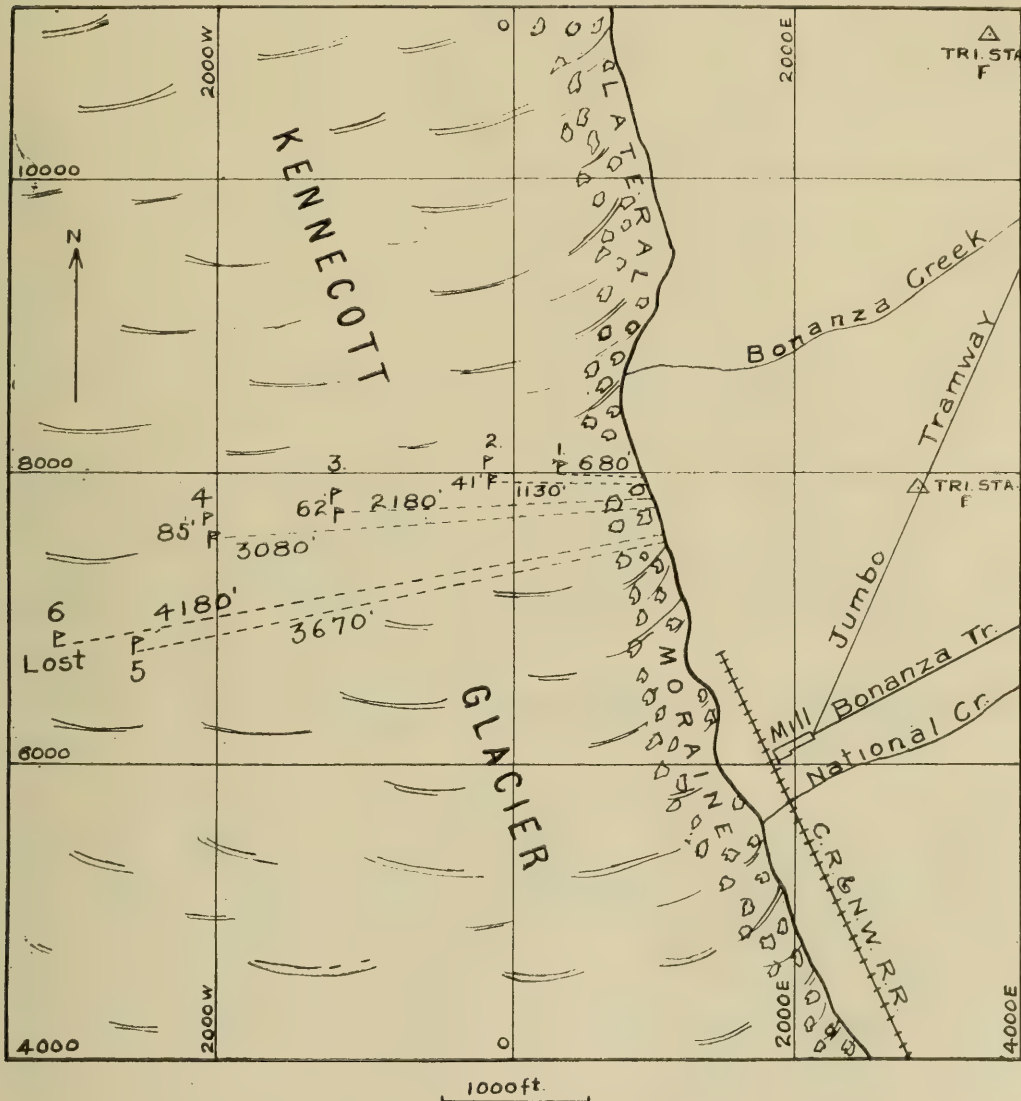


FIGURE 6.—Map showing Position of Stakes and Movement of Kennecott Glacier

After original drawing and plotting by D. C. Hoyt, Kennecott, Alaska.

exigencies of travel over the glacier and because the method of recording did not require it. The distances of the stakes from the edge of the glacier ranged from 680 to 4,180 feet. The total width at this point is approximately 17,000 feet. Some of the flags unfortunately disappeared,

probably due to the formation of crevasses. A base line and triangulation stations were established on the adjacent land, and by means of a surveyor's transit the positions of the flags were accurately measured from the triangulation stations. The readings were recorded and plotted by means of coordinates.⁸

The positions were first measured on September 28, 1918. The same triangulation stations were again occupied on September 21, 1919, 358 days later, but unfavorable weather prevented the completion of the measurement. Sixteen days later (October 7, 1919) triangulation stations were again occupied and the final measurements taken. All of the readings were then plotted by coordinates on the accompanying map (figure 6). An attempt was made to obtain further measurements the following year, but the stakes had disappeared.

RESULTS

The data of movement for the 374-day period are shown below, as are also the data for the shorter period.

Stake.	Distance from edge.	Period.	Total movement.	Movement per day.
1	680 feet.....	374 days.....	19.0 feet.....	0.61 inches
2	1,130 feet.....	374 days.....	41.5 feet.....	1.33 inches
3	2,180 feet.....	374 days.....	61.5 feet.....	1.97 inches
4	3,080 feet.....	374 days.....	85.0 feet.....	2.73 inches
3	2,180 feet.....	16 days.....	1.2 feet.....	0.87 inches
4	3,080 feet.....	16 days.....	1.9 feet.....	1.40 inches
5	3,670 feet.....	16 days.....	5.0 feet.....	3.77 inches

DISCUSSION OF RESULTS

It is interesting to note that the daily rate of movement for the 16-day period at the end of September is much slower than for the whole year, by just about one-half. It will be observed that the rate of movement increases outward from the edge of the glacier, as would be expected. The curve (figure 7) was plotted to show the relation between the rate of movement and the distance outward. This curve is surprisingly close to a straight line, indicating a progressively uniform increase in rate with distance outward from the edge of the glacier.

The data show that the movement of Kennecott Glacier is unusually slow. It is measured in inches per day, as contrasted with movements of feet per day obtained from measurements of many glaciers. Incidental observations on other glaciers in this same section of Alaska suggests that

⁸ The writer is indebted to D. C. Hoyt, chief engineer, Kennecott Copper Corp., Kennecott, Alaska, for this work and results.

this rate of movement is in keeping with the movement of other Alaskan glaciers of similar type in this same section. Some of the coastal glaciers are known to have much greater movement, but it is to be remembered that their topographic and climatic setting differs from that of Kennecott Glacier.

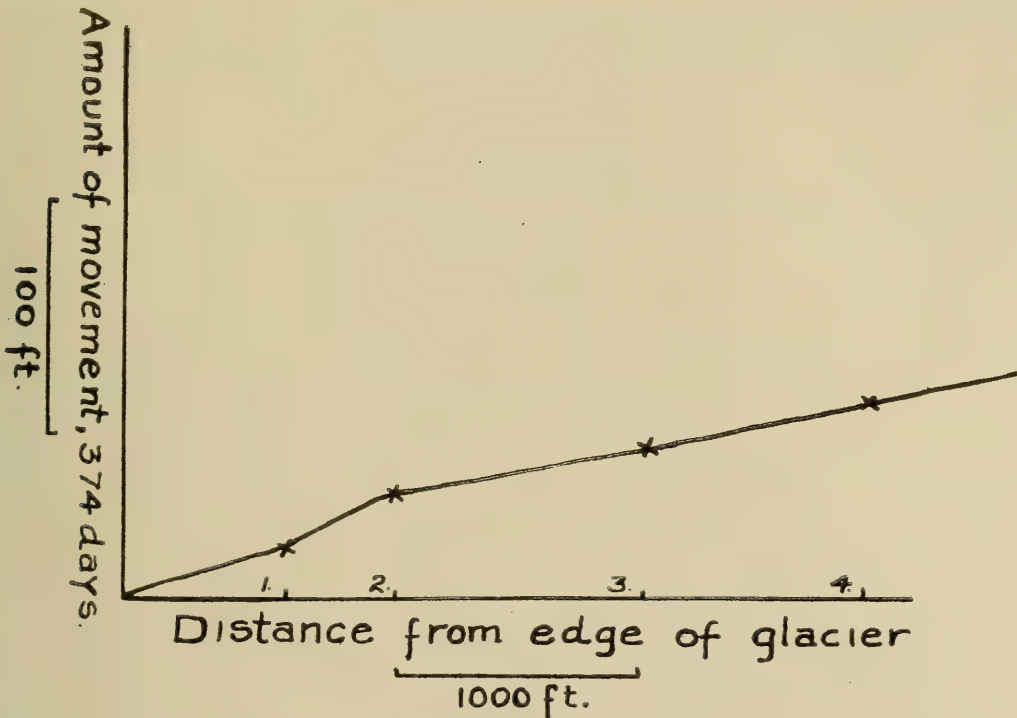


FIGURE 7.—Curve showing Relation between the Amount of Movement of Glacier and Distance from Edge of Glacier

The movement of Kennecott Glacier was measured at a point some 4 miles above its lower end, and is, therefore, a measurement of the body of the glacier. In this respect it differs from the measurements made on many of the Alaskan glaciers, where the advance or recession of the lower terminal only was considered.

MAP OF THE PLEISTOCENE LAKES OF THE BASIN-AND-RANGE PROVINCE AND ITS SIGNIFICANCE¹

BY OSCAR E. MEINZER

(Read before the Society December 29, 1921)

CONTENTS

	Page
Introduction.....	541
Pleistocene lakes.....	542
Present lakes and areas of ground-water discharge.....	545
Interpretation of Pleistocene climate.....	547
List of Pleistocene lakes in the Basin-and-Range Provinces.....	550

INTRODUCTION

The Basin-and-Range physiographic province, as outlined by a committee of the Association of American Geographers and the Physiographic Committee of the U. S. Geological Survey,² extends in the United States from southern Oregon to trans-Pecos Texas, and contains not less than 125 closed drainage basins—that is, basins which have no surface outlets for the water that falls upon them. The mountainous rims of these basins, with their great relief and remarkable exposures of geologic formations and structures, have, from the beginning of explorations in the region, compelled the attention of geologists. In contrast, the interior depressions of the basins, mantled by recent sediments and with surface features that are hardly discernible except by an experienced observer, have received relatively little attention and are commonly regarded as lacking in geologic interest. However, the serious work that has been done in these interior depressions, or basin valleys, has shown that they contain physiographic and hydrologic features of absorbing interest and much geologic significance, and also sufficient natural and artificial ex-

¹ Manuscript received by the Secretary of the Society February 23, 1922.

Submitted by permission of the Director of the U. S. Geological Survey.

² N. M. Fenneman: Physiographic divisions of the United States. *Annals Assoc. Amer. Geographers*, vol. 6, 1916, pp. 19-98. The north boundary of this province was slightly modified for the present paper in order to include Harney Valley, Oregon.

posures to afford important results in Tertiary and Quaternary stratigraphy, structure, and paleontology. I have spent a good many summers in these basin valleys, studying their water resources, and I am deeply impressed with the opportunity they present for further geologic work.

The early geologists were struck by the contrast between these basin valleys and the valleys in humid regions, and they did some memorable work in the valley areas which resulted in such classic papers as the Bonneville and Lahontan monographs. Later geologists working in the region, however, largely ignored the valleys or gave them only superficial attention. In recent years interest has been revived in these valleys through two lines of economic geology—the study of the ground-water resources of the desert region and the search for potash.

The main purpose of the present paper is to present a nearly complete map of the Pleistocene lakes of the Basin-and-Range Province which has resulted from this recent work. In addition, I will discuss briefly the relation of ground-water discharge by evaporation and transpiration in this province to the discharge from surface lakes, as developed by our recent water-resource investigations, and will call attention to studies of Pleistocene climate which I hope can be made in the future by comparing the Pleistocene with the present hydrology of the province.

PLEISTOCENE LAKES

The map of Pleistocene lakes presented herewith (figure 1) shows 68 ancient lakes, including the two giant lakes—Bonneville and Lahontan. A few Pleistocene lake beds probably still remain undiscovered, but for most of the region the map is complete. The ancient lakes were mapped chiefly by their shore features, many of which are still very conspicuous and distinct. In addition to the closed basins that held these lakes with definite shorelines, there are doubtless others that contained small ephemeral lakes which left no distinct shore features.

Somewhat more than half of these lakes were mapped by Russell and Gilbert many years ago, but about 25 have been mapped (and, for the most part, discovered) in recent years in connection with the ground-water and potash investigations of the U. S. Geological Survey. It should be noted that the newly mapped lakes are distributed over a large region which had previously been almost unexplored for these features, and that they represent a wide range in latitude, altitude, and climate. They are, therefore, especially significant in the interpretation of the hydrology and climate of the epoch in which they existed. The lakes mapped by Russell and Gilbert were found in northern and middle Nevada and adjacent

parts of Utah, Oregon, and California; the recently mapped lakes were distributed through middle and southern Nevada, southern California, and the parts of Arizona and New Mexico that lie in this province. Moreover, nearly all parts of the province that are devoid of Pleistocene lake beds have been examined for these features in recent years.

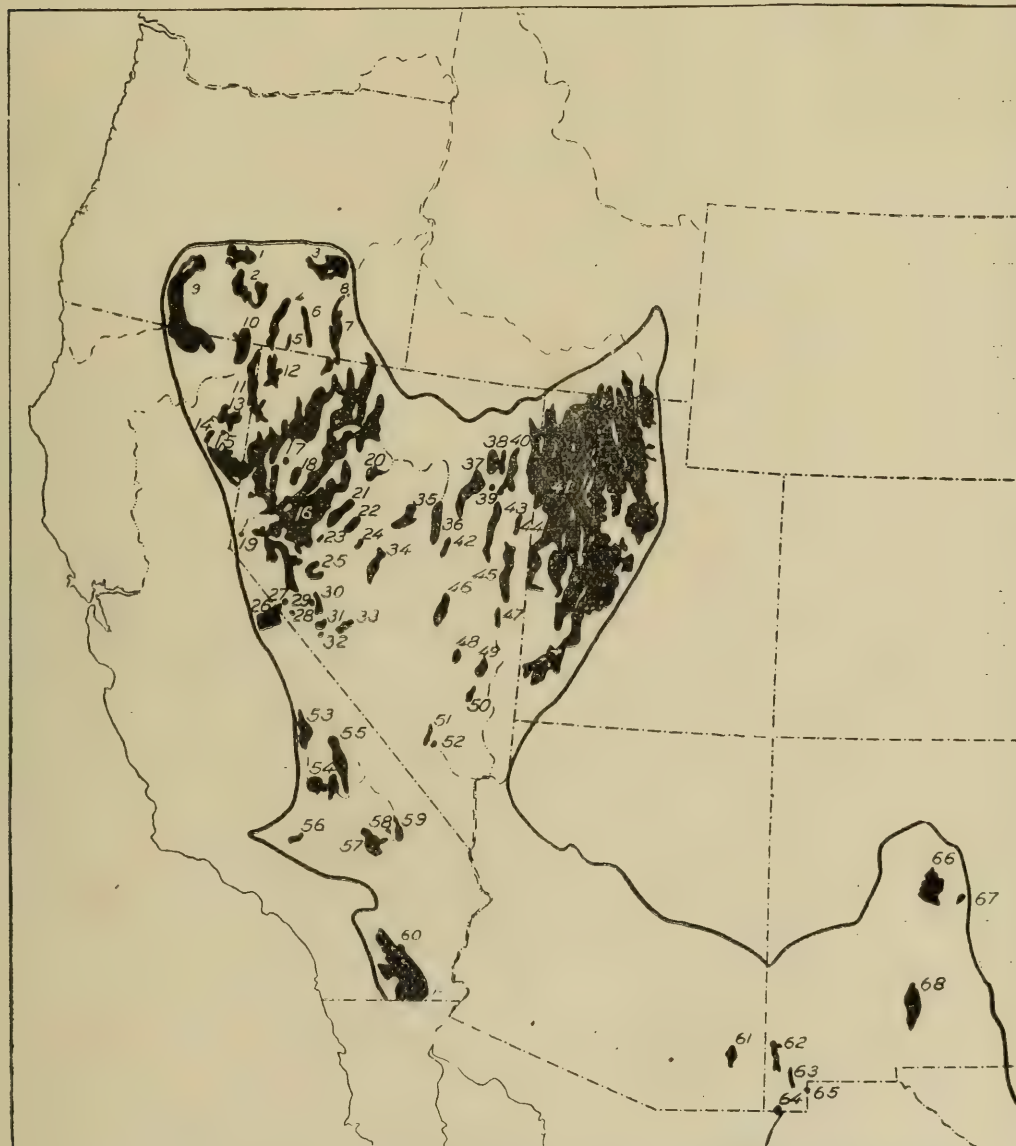


FIGURE 1.—Map of the Pleistocene Lakes in the Basin-and-Range Province

The presence or absence of Pleistocene lakes in a given drainage basin and the size of each lake relative to the size of its basin are conditions controlled by a number of rather complexly interrelated factors, such as the size of the basin, the permeability or impermeability of its bedrocks,

its altitude, relief, and topography, and the latitude and climatic belt in which it lies.

The map shows very plainly the relation of latitude to the size and abundance of lakes. There is at present a general southward increase in the rate of evaporation and decrease in precipitation. The distribution of the Pleistocene lakes shows that at the time they existed there was a comparable southward change in at least one of these factors. The northern part of the province was crowded with Pleistocene lakes, most of them of good size; farther south the lakes were smaller and less abundant, and some large basins contained no lakes of sufficient size and permanence to leave distinct shore features. In southwestern Arizona lakes were absent, because there were no closed basins that could hold lakes, but in southeastern California and trans-Pecos Texas closed basins occurred, and the absence or scarcity of lakes in these parts of the province was apparently due to aridity.

The map also affords good examples of the influence of altitude, relief, and topography on the existence and size of the lakes. The rapid transition from central Nevada, with its abundant Pleistocene lakes, to the relatively desiccated region of southern Nevada and southeastern California is largely due to rapid decrease in altitude with great increase in temperature and evaporation. Lake Estancia, in central New Mexico, whose strand is 6,200 feet above sealevel, was one of the highest of the Pleistocene lakes, and consequently, though it lies far south, it occupied 22½ per cent of its drainage basin. Lakes Bonneville and Lahontan evidently owed their great size to the productivity of the lofty Wasatch Mountains and Sierra Nevada, respectively. Lake Bonneville occupied 38 per cent of its basin and then overflowed. Lake Lahontan occupied about 20 per cent of its basin, the smaller percentage being due largely to the extensive area of relatively low, unproductive country east of the lake that was included in its drainage basin. Aside from the effects of altitude and relief in influencing evaporation and precipitation, the shape of the drainage basin is important in concentrating the surface waters in one locality, where they may accumulate to form a lake, or spreading them to such an extent that they are dissipated without forming a lake. The most striking example of the effect of concentration of the drainage is afforded by the Salton Sea, which developed rapidly in the midst of an intensely arid region when the Colorado, with its vast drainage basin, became tributary to it. The ancient lake in Coal Valley, Nevada, is another good example of this kind on a smaller scale.

PRESENT LAKES AND AREAS OF GROUND-WATER DISCHARGE

Figure 2 is a map of the Basin-and-Range Province showing approximately the lakes that exist in this province at the present time. As most of these lakes lie on very flat bottoms of the ancient lakes, they fluctuate

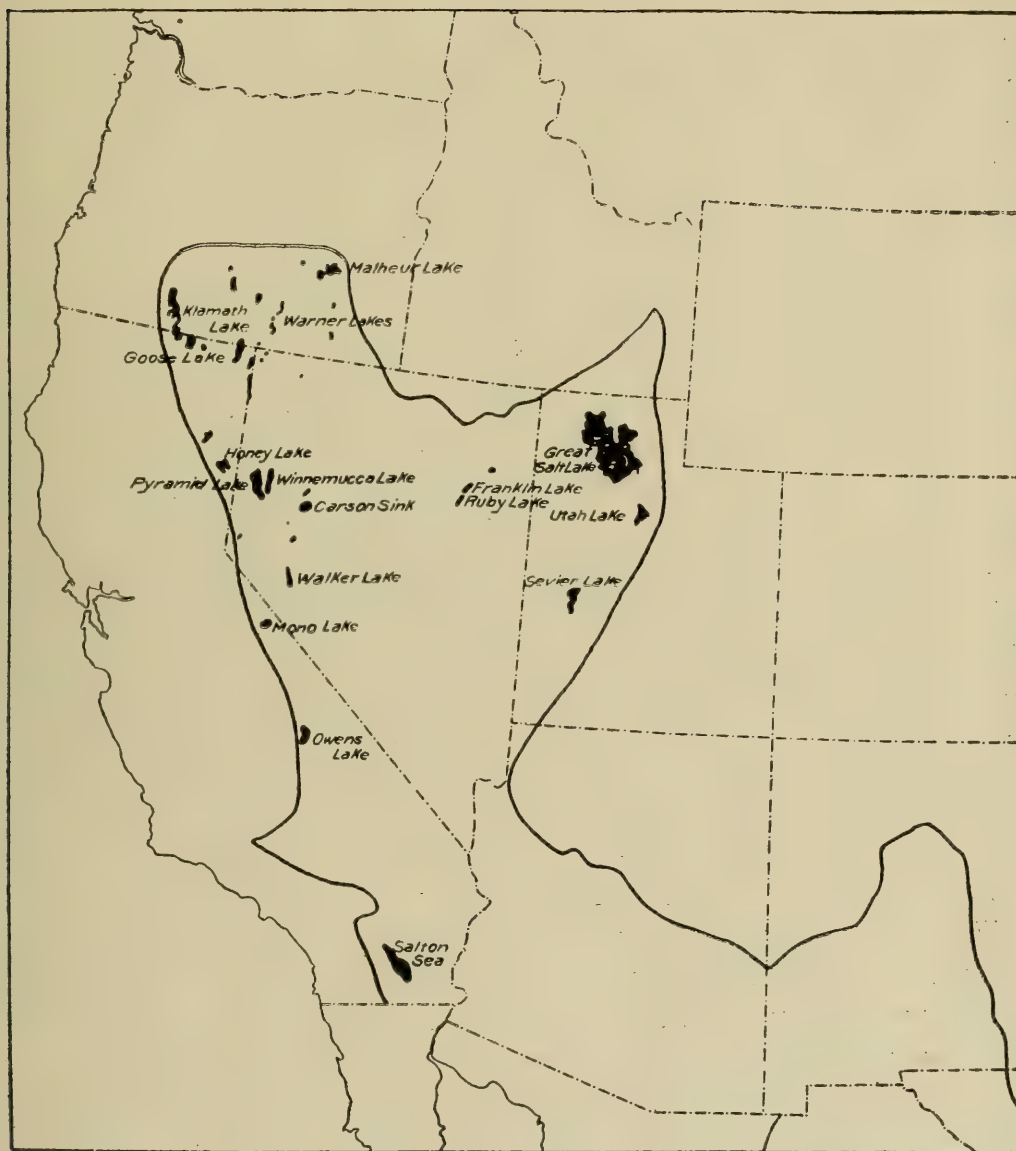


FIGURE 2.—Map of the present Lakes in the Basin-and-Range Province

greatly in area with the changing seasons. For this reason they are more difficult to map than are the ancient lakes, which had more definite shorelines.

The region is at present not nearly so destitute of a water supply as has often been assumed or as might be inferred from this map. The

basins are of three types: (1) those in which lakes still exist, (2) those which do not have lakes, but are discharging water from the subterranean reservoirs into the atmosphere by evaporation and transpiration, often in large quantities, and (3) those which do not have lakes and in which, moreover, the water-table is everywhere so low that they do not discharge ground-water except by subterranean leakage out of the basin. A basin with ground-water discharge has a different aspect from one without such discharge and it functions differently. Instead of being completely desiccated except in brief rainy seasons, as was the conception once usually held, it may in fact contain a vast reservoir of ground water that is discharging large quantities of water by evaporation and by transpiration from plants throughout all the dry, hot, summer season, though no water may be visible at the surface. Only a few of the basins at the present time have perennial lakes that are discharging water by evaporation, but many of them have extensive areas of ground-water discharge. Data are being accumulated for constructing a map of the areas of ground-water discharge in the Basin-and-Range Province. This map will probably show that, excepting the basins of Lakes Bonneville and Lahontan, the aggregate area at present discharging water by evaporation and transpiration from ground-water reservoirs is not greatly inferior to the aggregate area which in the Pleistocene was discharging by evaporation from lakes. The north basin of Big Smoky Valley, Nevada, may serve to illustrate the importance of ground-water discharge (figure 3). In this basin there is an area of 160 square miles in which ground water is being discharged into the atmosphere. The average rate of discharge in this area has been roughly estimated to be 6 inches of water a year, which would amount to about 50,000 acre-feet a year, or 45 million gallons a day—about 8 per cent of the water that falls on the basin as rain or snow.

While the aggregate discharge of ground water is a very large quantity, it should be noted that the rate of discharge is much lower than the rate of evaporation from a lake under the same atmospheric conditions. If the average annual evaporation from a free water surface in Big Smoky Valley is 60 inches and the average annual rate of loss from the area of ground-water discharge is only 6 inches, then the ground-water discharge is equal to the evaporation from a lake of 16 square miles occupying $1\frac{1}{4}$ per cent of the drainage basin. The Pleistocene lake in this basin occupied 225 square miles, or 18 per cent of the basin (figure 4). The quantity of water that would be discharged by evaporation from a lake of this size under present climatic conditions would, according to the assumptions made, be about 14 times the present ground-water discharge and

would be greater than the entire quantity of water that falls on the basin as rain or snow.

INTERPRETATION OF PLEISTOCENE CLIMATE

I believe these basins afford a feasible approach to the problem of past climate that has not been exploited. I hope that with further work it

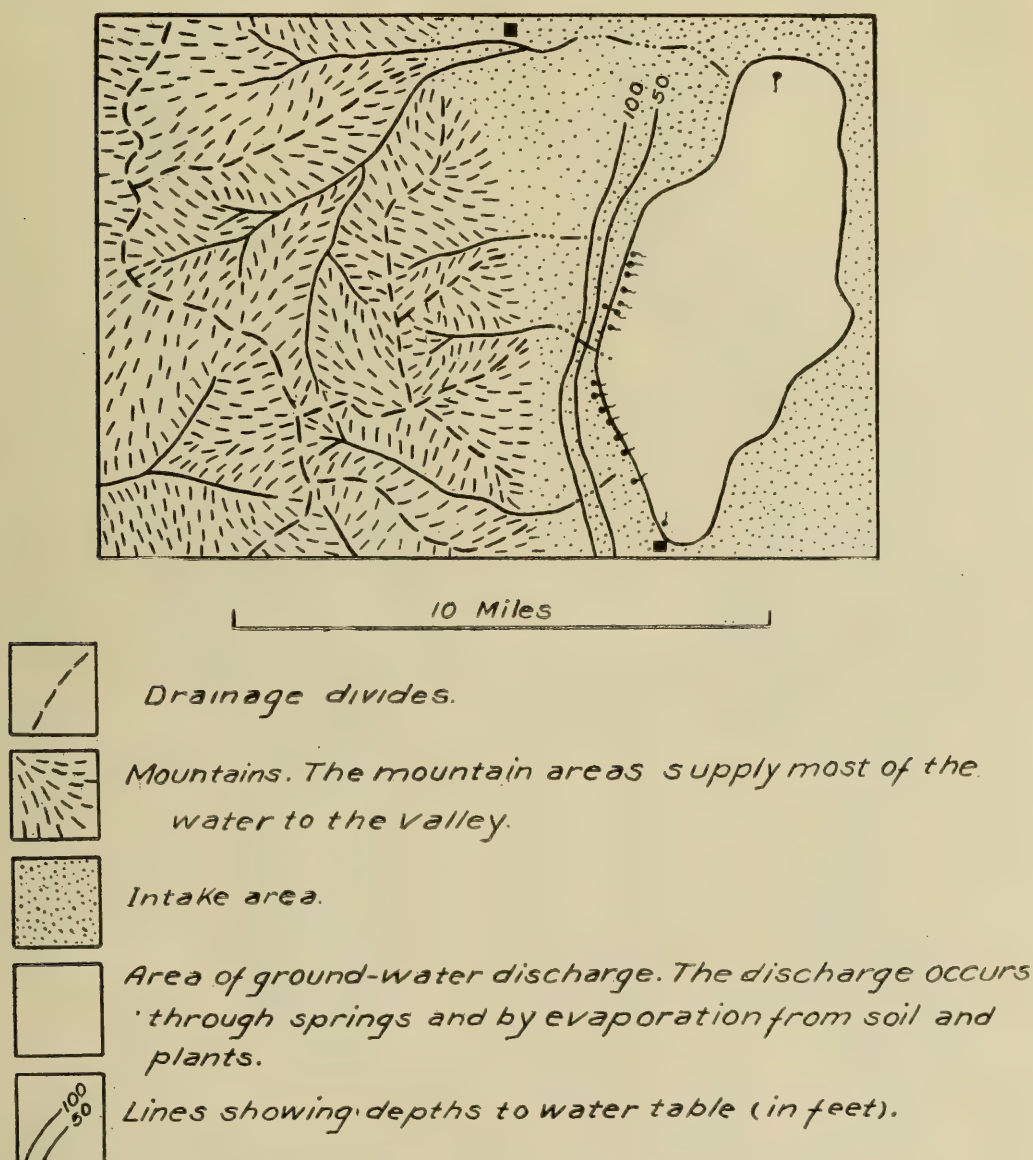


FIGURE 3.—Map of Part of the North Basin of Big Smoky Valley, Nevada
Showing intake and discharge areas.

will be possible to make a quantitative estimate of Pleistocene climate by comparing the Pleistocene and present hydrology of the basins. The problem is, indeed, rendered complex by the variables that are involved

and especially by the fact that the unknown quantity (Pleistocene climate) contains at least two unknown factors—temperature and precipitation. But, on the other hand, it is made tangible by the large number



FIGURE 4.—*Map comparing the Pleistocene Lake and the Present Areas of Ground-water Discharge in the North Basin of Big Smoky Valley, Nevada*

Figure on left represents present area of ground-water discharge, 160 square miles.

Figure on right represents the Pleistocene lake, 225 square miles.

and convenient variety of basins, by the fact that these basins are so nearly independent of one another that they lend themselves well to com-

parison, and by the fact that the topography of the basins has changed very little since the ancient strands were formed.

The range in humidity (or aridity) among the various basins in the Pleistocene epoch was apparently as great as the difference in a given basin between the Pleistocene and the present. A considerable number of the closed basins in the province were too arid in the Pleistocene to contain lakes of any consequence, whereas a few are humid enough at present to contain perennial lakes of considerable size. The relatively humid parts of the province at the present time seem to be comparable to the most arid parts in the Pleistocene epoch (compare figures 1 and 2). The region of southwestern New Mexico and southeastern Arizona in the Pleistocene is apparently comparable to southern Oregon at present, for the Pleistocene lakes near the Mexican border do not seem to amount to much more than do the present lakes of Oregon. The south end of Nevada in the Pleistocene can perhaps be compared to northeastern Nevada at present, with its few small lakes, the difference in latitude here being less than in the first case because there is a great difference in altitude. Parts of southeastern California and trans-Pecos Texas in the Pleistocene can perhaps be compared to parts of Nevada at present where the climate is just too arid for perennial lakes. Lastly, the Pleistocene lakes of the somewhat dismembered Death Valley basin, including the Owens, Amargosa, and Mohave River drainage basins, seem to have their approximate counterparts in the existing remnants of Lake Lahontan.

These generalizations are, of course, interesting rather than accurate, but they suggest a somewhat tangible method of attack. That they involve a substantial difference in climate is shown by the fact that in each of the four comparisons that have been made there is at present a difference in mean annual temperature between the regions compared of more than 15 degrees Fahrenheit. What is needed for even an approximate solution of the problem is adequate topographic maps of the basins, a general knowledge of their rock formations and structures, complete maps and data regarding their Pleistocene and present lakes and their present areas of ground-water discharge, adequate data as to the physiographic changes that have taken place in them since the Pleistocene, and abundant records of their temperature, precipitation, stream flow, evaporation, and ground-water discharge.

LIST OF PLEISTOCENE LAKES IN THE BASIN-AND-RANGE PROVINCE
(SEE MAP, FIGURE 1)

(Asterisk indicates lake that had outlet)

Map number.	Name of lake or of containing valley or basin.	Principal authorities.	References.
1	Silver and Christmas.	I. C. Russell.....	U. S. Geological Survey, Fourth Annual Report, plate LXXXIII.
		G. A. Waring....	Water-Supply Paper 220.
2	Abert and Summer...	do.....	do.....
*3	Harney	do.....	Fourth Annual Report, plate LXXXIII; Water-Supply Paper 231.
4	Warner	do.....	Fourth Annual Report, plate LXXXIII; Water-Supply Papers 220 and 231.
5	Guano	I. C. Russell.....	Fourth Annual Report, plate LXXXIII.
6	Catlow	do.....	Fourth Annual Report, plate LXXXIII.
		G. A. Waring....	Water-Supply Paper 231.
7	Alvord	do.....	do.....
8	.....	I. C. Russell.....	Fourth Annual Report, plate LXXXIII; Eighth Annual Report, plate XVI; U. S. Geological Survey Monograph XI, plate I.
*9	Klamath	do.....	do.....
*10	Goose	do.....	Fourth Annual Report, plate LXXXIII.
		G. A. Waring....	Water-Supply Paper 220.
11	Surprise	I. C. Russell.....	Monograph XI, plate XLVI.
12	Long	do.....	do.....
*13	Madeline	do.....	do.....
*14	Eagle Lake.....	do.....	do.....
*15	Horse Lake.....	do.....	do.....
16	Lake Lahontan.....	do.....	Third Annual Report, plate XVIII; Monograph XI, plate XLVI.
17	.....	.....do.....	Monograph XI, plate XLVI.
18	Granite Spring.....	do.....	do.....
*19	Washoe	do.....	do.....
*20	Buffalo Springs.....	do.....	do.....
21	Osobb, Dixie, or Humboldt Salt Marsh...	do.....	do.....
22	Edwards Creek.....	do.....	do.....
23	Fairview	do.....	do.....

Map number.	Name of lake or of containing valley or basin.	Principal authorities.	References.
24	Smith Creek.....	I. C. Russell.....	Monograph XI, plate XLVI.
25	Gabbs	do.....	do.....
26	Mono Lake.....	do.....	Monograph XI, plates I and XLVI; Eighth Annual Report, plate XVI.
27	.....	do.....	Monograph XI, plate XLVI.
28	.....	do.....	Monograph XI, plate XLVI.
29	Excelsior Flat.....	do.....	do.....
30	Spring	do.....	do.....
31	Columbus Salt Marsh.	I. C. Russell.....	Monograph XI, plate XLVI.
		H. S. Gale	U. S. Geological Survey Professional Paper 95, figure 1.
		W. B. Hicks	
32	.....	I. C. Russell.....	Monograph XI, plate XLVI.
33	Big Smoky (Lake Tonopah)	O. E. Meinzer....	Water-Supply Paper 375, plate VII; Water-Supply Paper 423, plate I.
34	Big Smoky (Lake Toyabe)	I. C. Russell.....	Monograph XI, plate XLVI.
		O. E. Meinzer....	Water-Supply Paper 375, plate VI; Water-Supply Paper 423, plate I.
35	.....	I. C. Russell.....	Monograph XI, plate I; Eighth Annual Report, plate XVI.
*36	Diamond	do.....	do.....
37	Ruby	do.....	do.....
38	Clover	do.....	do.....
39	Butte	W. O. Clark and C. W. Riddell....	Water-Supply Paper 467, plate III.
40	Goshute	I. C. Russell.....	Monograph XI, plate I; Eighth Annual Report, plate XVI.
*41	Lake Bonneville.....	G. K. Gilbert....	Second Annual Report, plate XLII; Monograph I.
42	Newark	I. C. Russell.....	Monograph XI, plate I; Eighth Annual Report, plate XVI.
*43	Steptoe	W. O. Clark and C. W. Riddell....	Water-Supply Paper 467, plate III.
44	Antelope	do.....	do.....
45	Spring	do.....	do.....
46	Railroad	E. E. Free.....	Mining and Scientific Press, volume 107, page 176; U. S. Department of Agriculture Bulletin 54, pages 35 and 36.
		Everett Carpenter	Water-Supply Paper 365, plate I.
*47	Duck	do.....	do.....
48	Coal	do.....	do.....

Map number.	Name of lake or of containing valley or basin.	Principal authorities.	References.
49	Bristol	Everett Carpenter	Water-Supply Paper 365, plate I.
50	Delamar	do.....	do.....
51	Indian Spring.....	do.....	do.....
*52	.....	do.....	do.....
*53	Owens	H. S. Gale.....	U. S. Geological Survey Bulletin 580, plate VII.
*54	Indian Wells, Salt, Wells, and Searles..	do.....	do.....
*55	Panamint	do.....	do.....
56	Antelope	D. G. Thompson..	Water-Supply Paper (in preparation).
*57	Mohave (Lake Manix)	J. P. Buwalda...	University of California Publication Bulletin, Department of Geology, volume 7, number 24, plate XXII.
58	Cronise (Little Mohave Lake).....	D. G. Thompson..	Water-Supply Paper (in preparation) ; Journal of Washington Academy of Sciences, volume 11, page 424.
*59	Silver and Soda (Lake Mohave)	do.....	do.....
60	Salton Sea.....	W. P. Blake.....	Report of exploration and survey for railroad, Senate Executive Document 78, Thirty-third Congress, Second Session, volume 5, part 2.
		W. C. Mendenhall	Water-Supply Paper 225, Plate I.
61	Sulphur Spring (Lake Cochise)	O. E. Meinzer....	Water-Supply Paper 320, plate I.
62	Animas	A. T. Schwennesen	Water-Supply Paper 422, plate I.
63	Playas	do.....	do.....
64	San Luis (Lake Cloverdale)	Ellsworth Hunt-	Carnegie Institute of Washington..... ington, Publication 192, page 70.
		A. T. Schwennesen	Water-Supply Paper 422, plate I.
65	Hachita	do.....	Water-Supply Paper 422, plate I.
66	Estancia	O. E. Meinzer....	Water-Supply Paper 275, plate I.
67	Encino	do.....	Water-supply Paper 275, plate XII.
68	Tularosa (Lake Otero)	R. S. Tarr.....	American Naturalist, volume 25, page 524.
		C. L. Herrick....	American Geologist, volume 34, page 185.
		O. E. Meinzer....	Water-Supply Paper 343.

RECONNAISSANCE OF THE EASTERN ANDES BETWEEN COCHABAMBA AND SANTA CRUZ, BOLIVIA¹

BY KENNETH C. HEALD AND KIRTLEY F. MATHER

(Presented before the Society by the Senior Author December 29, 1921)

CONTENTS

	Page
Introduction.....	553
Physiography.....	555
The area examined.....	555
The Cordillera Oriental.....	555
Santa Cruz plains.....	556
Stratigraphy.....	558
Character of the rocks.....	558
Arani formation.....	558
Totora formation.....	559
Maternal formation.....	560
Bermejo formation.....	561
Cajones limestone.....	565
San Ysidro formation.....	567
Quaternary.....	569
Structure.....	569

INTRODUCTION

The eastern Andes of central Bolivia were crossed by the authors in December, 1919, during the progress of geological exploration for Richmond Levering and Company, whose courtesy makes this paper available. The observations made during the traverse, 200 miles long and 10 days in duration, between Cochabamba, on the west, and Santa Cruz, on the east, were rendered more comprehensive and understandable by subsequent work north and south of Santa Cruz, along the east front of the mountains.

Our exploratory expedition left Cochabamba on December 3 and proceeded by train to Arani, the terminus of a short narrow-gauge railway, which now (October, 1921) is being extended farther eastward toward

¹ Manuscript received by the Secretary of the Society February 3, 1922.

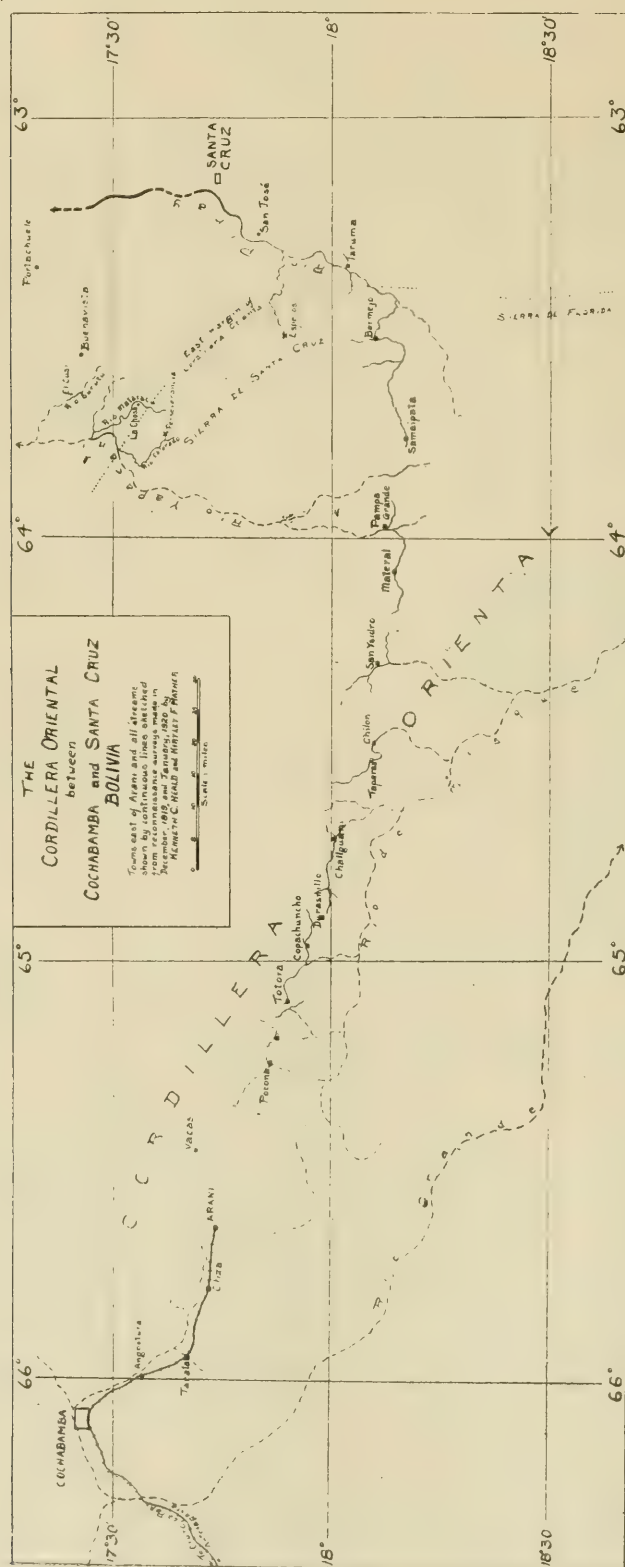


FIGURE 1.—The Cordillera Oriental between Cochabamba and Santa Cruz, Bolivia

Totora. From Arani we traveled by mule train across the successive ranges of the Cordillera Oriental past Totora, Chilon, Pampa Grande, and Samaipata to Santa Cruz, which was reached the evening of December 13 (see figure 1). The necessities of rapid travel rendered impossible the detailed examination of many tempting exposures, but it is believed that the data found on this trip will nevertheless prove of some value. The following week we made a hasty visit to the famous oil seepage in Espejos Canyon, in the foothills of the Andes, 30 miles southwest from Santa Cruz. Finally, between December 25 and January 11, a number of days were spent in the vicinity of Rio Colorado; likewise in the Andean foothills near the small hamlet known as Buenavista.

PHYSIOGRAPHY

THE AREA EXAMINED

The area which we were thus permitted to examine ranges in altitude from about 14,000 to about 1,000 feet above sealevel. The greater part of it is within the boundaries of the Cordillera Oriental, or Eastern Range of the Andes, but the eastern portion extends out upon the Santa Cruz Plains. Each of these two strongly contrasting regions forms one of the major physiographic provinces of Bolivia.

THE CORDILLERA ORIENTAL

During late Tertiary (?) time this area was a low-featured peneplain, which is now represented only by ridge-tops and a few undissected remnants. The peneplain was tilted so that its western edge, near the town of Arani, was at an altitude of more than 13,000 feet, while its eastern margin, at the crest of the easternmost range of the Andes, was at an altitude of less than 3,000 feet. The major streams of the region were probably developed on this old peneplain. That they antecede the present cycle is abundantly shown by their disregard of structural and stratigraphic conditions. Apparently dissection of the peneplain started near its eastern margin. The highlands on the west, near Arani, are very little modified by stream erosion, whereas most of the area to the east has been maturely dissected. Stream valleys in the area between Pocona and Samaipata are moderately broad, with flat alluvium-filled bottoms, and their sides, although precipitous in many places and everywhere steep, culminate in narrow divides, with but slight suggestion of the plateau surface that must have preceded the present cycle (see figure 2). East and north of Samaipata, in the easternmost of the Andean ridges, where the exposed strata are in large part massive red sand-

stones, the streams traverse deep box canyons, the walls of which rise abruptly from the edges of the swift torrents (see figure 3). However, the existence of the peneplain is still evidenced by the uniformity in elevation of individual ridges, the general absence of prominent peaks regardless of the differing natures of the various geological formations, the uniform decline in elevation from ridge-top to ridge-top progressively toward the east, and by a few plateau-like remnants. Nowhere in the area between Arani and Santa Cruz is there evidence of Pleistocene glaciation.



FIGURE 2.—Cochabamba-Santa Cruz Geology

The barren rounded heights of the Andes, 13,000 to 14,000 feet above the sea, carved in Arani sandstones and shales a few miles south of Vacas, on the Santa Cruz trail.

SANTA CRUZ PLAINS

To the east of the mountains the country is quite flat and poorly drained. Its elevation is between 1,200 and 1,800 feet above sealevel. A few major streams cross the plains, but side streams flow only during the rainy season, and in other times are represented merely by sand-covered courses. Such rivers as the Piray and Surutu flow in shallow valleys bordered by low hills, some three or four miles apart. Over much of this flat area the rain water collects where it falls, with practically no run-off, and makes bogs and morasses. Stream channels are almost invariably floored with treacherous quicksands.

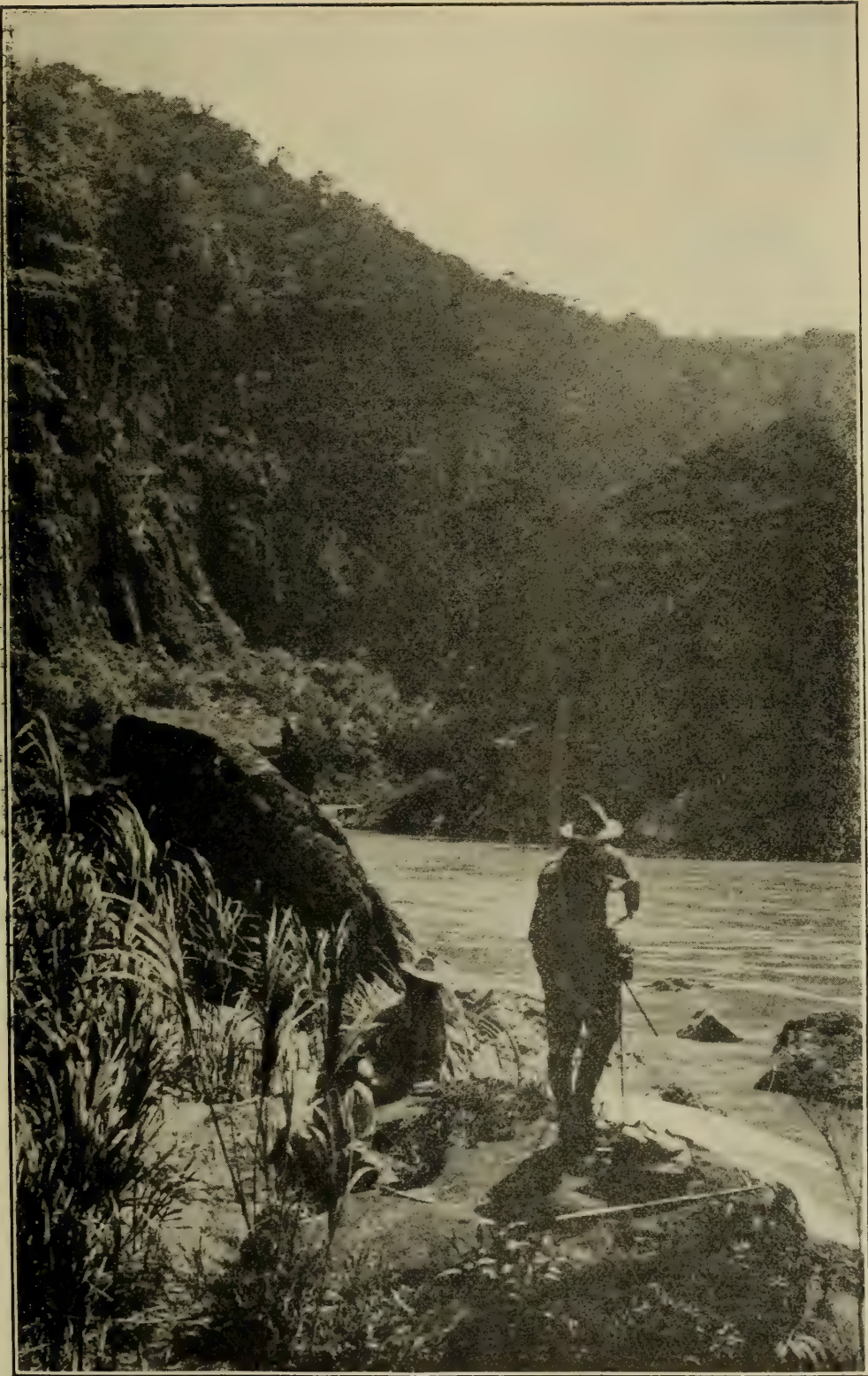


FIGURE 3.—*Cochabamba-Santa Cruz Geology*

The canyon of Rio Colorado cut in massive Bermejo red beds, just within the Sierra de Santa Cruz near Buenavista.

At many localities, especially within a few miles of the mountain front, there are numerous low hillocks which were undoubtedly once sand-dunes, but whose migration has been stopped by the growth of grass and trees. Between these irregular mounds there is little drainage and in rainy weather there are many shallow ponds without outlets.

STRATIGRAPHY

CHARACTER OF THE ROCKS

The rocks in this region are dominantly sandstones and shales. They range in age from Devonian to Pleistocene and have an aggregate thickness of at least 30,000 feet, and perhaps double that. No intrusive rocks were seen, nor was there evidence in the stream gravels that any considerable body of such rocks exists in the general region passed through. The oldest rocks in the stratigraphic section examined are metamorphosed to a certain extent, but the metamorphism is comparatively slight. Some of the sandstones are quartzitic, but interbedded shales are not greatly indurated. Shales predominate throughout the section, although there are also great thicknesses of sandstone, with minor amounts of conglomerate, tillite, and limestone, and also surficial deposits, such as stream gravels, sands, and clays.

ARANI FORMATION

The oldest rocks in the section studied were called the Arani formation by the writers because of their excellent exposures in the abrupt slopes that rim the Arani Basin. A small collection of brachiopods obtained from a quartzitic sandstone some two miles north of the town of Arani indicates that these beds are Devonian in age. The entire thickness of the formation could not be estimated. It is known to exceed 3,000 feet and probably totals three or four times that thickness. It is composed of quartzites, quartzitic sandstone, and indurated shales. The quartzites commonly weather to a rusty reddish color, although freshly broken surfaces are dark gray or bluish gray, with occasional pinkish tints. They are extremely hard, dense, and break with a conchoidal fracture. Individual beds range in thickness from a few inches to 7 or 8 feet, with an average less than a foot.

The quartzitic sandstones are similar in appearance to the quartzites, but are less dense. Many of the sandstone beds show spheroidal concretionary structures, which weather into concentric circles that may be as much as 6 feet in diameter.

The shales are commonly brown or reddish brown on weathered sur-

faces, although the fresh surfaces are dark gray. They are in thin beds, are well laminated, and are characterized by numerous joints approximately at right angles to the bedding. They are quite sandy and were not observed to have any limy partings, inclusions, or concretions, nor were any fossils found in them. They are so indurated as to be more or less slaty in places.

The fossils found near Arani show that this formation originated, at least in part, under marine conditions. The abundance of the sandstone and the sandy character of the shales are evidence of near-shore deposition, and possibly they are in part continental in origin. Absence of conglomerates and coarse material argues against any pronounced relief in the area rimming the basin in which the Arani beds were deposited, or at least supports the belief that the depositing currents were comparatively slow-moving. It is thought that this formation accumulated in the sinking basin of an epicontinental sea surrounded by featureless lowlands. Absence of limestones and scarcity of fossils suggest that the climate was rather cold, although the muddiness or siltiness of the water may have been responsible for scarcity of marine life.

TOTORA FORMATION

Overlying the Arani formation is a succession of sandstones and shales that differ so much in appearance from the underlying beds that it is unquestionably justifiable to consider them an independent unit, although no sharp break was proven to exist between them and the Arani beds. For this succession of beds the name "Tоторa formation" is suggested, as it is characteristically developed near the town of that name.

The age of the formation is established as Devonian by a number of fossil collections. These fossils are all marine and in places are extremely numerous. Brachiopods are particularly abundant.

The total thickness of the Tоторa formation is estimated as 10,000 feet. This is an extremely rough approximation, as no detailed measurement was possible when the observations were made. The rocks of the formation were first seen about four miles east of Tоторa, and they surfaced most of the area between Tоторa and Samaipata, 100 miles to the east.

The formation consists dominantly of dark shales, with thin beds of clayey sandstones and quartzitic sandstones, and, near the top of the formation, a few massive sandstones. Float from at least one limestone bed was seen, although no outcrops were observed.

The shales range in color from black through bluish gray to light gray. A few beds with a reddish tint were seen, but they are very rare.

The light gray beds are gypsiferous and contain many limestone concretions. A series of ferruginous shales, gray, brown, and reddish in color, is doubtfully placed in the upper portion of this formation. Both shales and thin sandstones are very micaceous. The mica ranges from microscopic specks to flakes an eighth of an inch in their greatest dimension.

The sandstones through most of the formation are so thin as to be almost unnoticeable, single beds averaging only a few inches in thickness and aggregate thicknesses of contiguous sandstone beds being commonly less than four feet. Many of these thin sandstones are richly fossiliferous.

The upper part of the formation is much more sandy than is the base. This is shown both by an increase in the sand content of the shales and by the presence of massive beds of sandstone. These massive sandstones are gray to tan in color, close textured, fine grained, and moderately hard. Individual beds may be as thick as 50 feet, although the average is much closer to 10 feet.

The Totora is lithologically quite similar to the Pennsylvanian strata of southeastern Oklahoma and, probably like these Pennsylvanian strata, originated by practically continuous sedimentation in a shallow sea, the floor of which sank steadily under the accumulating load of sand and mud.

MATERAL FORMATION

The Maternal formation, named from the village of Maternal, on the Santa Cruz Trail, is believed to rest unconformably on the Totora, although this unconformability was not actually observed. However, the striking difference in lithology of the two formations signifies very different conditions of sedimentation or sources of materials and supports a belief in a time break between the two formations.

The age of the Maternal was not determined, but it is ascribed to the Carboniferous because of its relation to the underlying Totora beds and to the overlying Bermejo formation, which is thought to be Permian. However, it must be recognized that the age of the Bermejo is also in doubt.

The thickness of the formation could not be closely estimated, for folding and faulting had complicated the section where the traverse crossed it. However, it may be confidently stated that this thickness exceeds 2,000 feet and very probably 4,000 feet.

The most prominent beds in the formation are heavy sandstones, although shales may predominate in aggregate thickness. No lime-

stones were seen. The sandstones are for the most part massive, fine textured beds, ranging in color from gray to red, with intermediate shades of yellow, tan, and brown. Some of them are conglomeratic, so there must also be some coarse sandstones, although none were specifically noted. One sandstone bed with a thickness of about 600 feet was seen, but the average thickness is probably 40 feet or less. Both sands and conglomerates are formed dominantly of white or colorless quartz. The conglomerates also contain some flesh-colored feldspar.

The shales are light colored, ranging through a variety of shades of gray, green, and red. No black shales like those of the Totorá formation are present, unless, indeed, an exposure about 10 miles east of Materral, which was believed to represent Totorá shale, unconformably below the Materral, should really be ascribed to the latter. All the shales seen appeared quite massive, with little fissility or lamination.

The outcrop of this formation is crossed by the Santa Cruz Trail between San Ysidro and Samaipata. A point midway on the exposure would be about 70 miles west and 25 miles south of Santa Cruz.

The Materral beds are thought to be continental in origin. The conglomerates are almost certainly fluviatile, and the red and green shales are probably in large part lake deposits. The perfect sizing and rounding of the grains in one sandstone bed suggested windwork, but supporting evidence, such as cross-bedding and ripple-marks, was lacking. The feldspar in the conglomerate suggests a different source for the materials that formed the Materral and those that make up the Totorá, and relates the Materral more closely to the overlying Bermejo formation, in which feldspar and fragments of granitic rock are locally abundant.

BERMEJO FORMATION

Unconformably above the Materral formation is a thick series of heavy sandstones, massive shales, and thin beds of tillite aggregating in thickness about 10,000 feet, which the writers have called the Bermejo formation after the settlement of Bermejo, near which it is developed.

The age of the Bermejo was not discovered. It is thought to be Permian, but the evidence for this assignation is inferential. The unconformity that separates it from the underlying formations is profound, probably representing in places the entire thickness of the Materral formation and much of the Totorá. The Bermejo is, therefore, unquestionably post-Devonian and probably post-Pennsylvanian. In the region to the south it lies below the Calcareo-dolomitico of Steinman, which he assigned to the Cretaceous on the basis of fossils. Its tillite beds suggest contemporaneity with similar deposits in Brazil, which Branner



FIGURE 4.—*Cochabamba-Santa Cruz Geology*

The massive sandstones of the Bermejo formation, exposed along the trail between Samaipata and Bermejo. The maroon and vermillion bed in which the alcove is weathered is over 200 feet thick.

has shown to be Permian, and the lithology of the sandstones suggests beds to which Permian age has been ascribed in the vicinity of Lake Titicaca, to the west. A few fossils were found in it, but, with the exception of some unidentifiable fragments, they were all lingulas, valueless for determining its stratigraphic position.

The sandstones of the Bermejo are massive and heavy bedded. One bed at least 300 feet thick, with no sign of either false or true bedding dividing it, was seen (see figure 4). For the most part the weathered surfaces are reddish brown, but grays and yellows are also present. The fresh surfaces are commonly yellow brown to gray, mottled with brown spots of limonite or manganese. The sandstones are composed of colorless, translucent quartz grains in a limy cement. Individual grains are well rounded, but are irregular in size, although for the most part very fine. Ripple-marks, rill-marks, mud cracks, worn borings, et cetera, were not observed. Many of the sandstones contained a sprinkling of pebbles, many of which were faceted by ice action, but no beds with enough pebbles to earn the title of conglomerate were seen where the Bermejo was crossed on this traverse.

These conspicuous sandstone beds have induced a topography individual to the Bermejo in this region—high cliffs with arched alcoves, peaks bounded by sheer rock, vertical walls crowning ridges that fall away in long, steep slopes, sharp-crested twisting divides and smooth-sloped hogback ridges prevail (see figures 4 and 5). The type of topography is not entirely due to lithology, but the influence of these resistant beds is everywhere apparent.

Probably about half the thickness of the formation is shale or indurate clay. These clays are commonly of a delicate lavender shade, particularly in the upper two-thirds of the formation. Near its base, dark gray and black replace the lavender, although other characteristics of the beds are quite similar. The beds are rarely laminated and weather much like massive sandstones. Under the hammer they break into irregular chunks, apparently obeying no laws of cleavage. Their toughness results in low cliff faces along streams or extremely steep slopes along valey sides, although these features are frequently modified by landslides, showing that the clays soften quite easily in water. Scattered through the clays are grains, pebbles, and cobbles of blue and gray quartzite and granitic rocks that are commonly beautifully faceted by ice action. There are also beds of true tillite² composed of angular rock fragments in argillaceous cement. Some of these rock fragments are

² A detailed description of these tillites will be given in a report on the glacial and fluvio-glacial deposits of the eastern Andes of Bolivia, now in preparation.

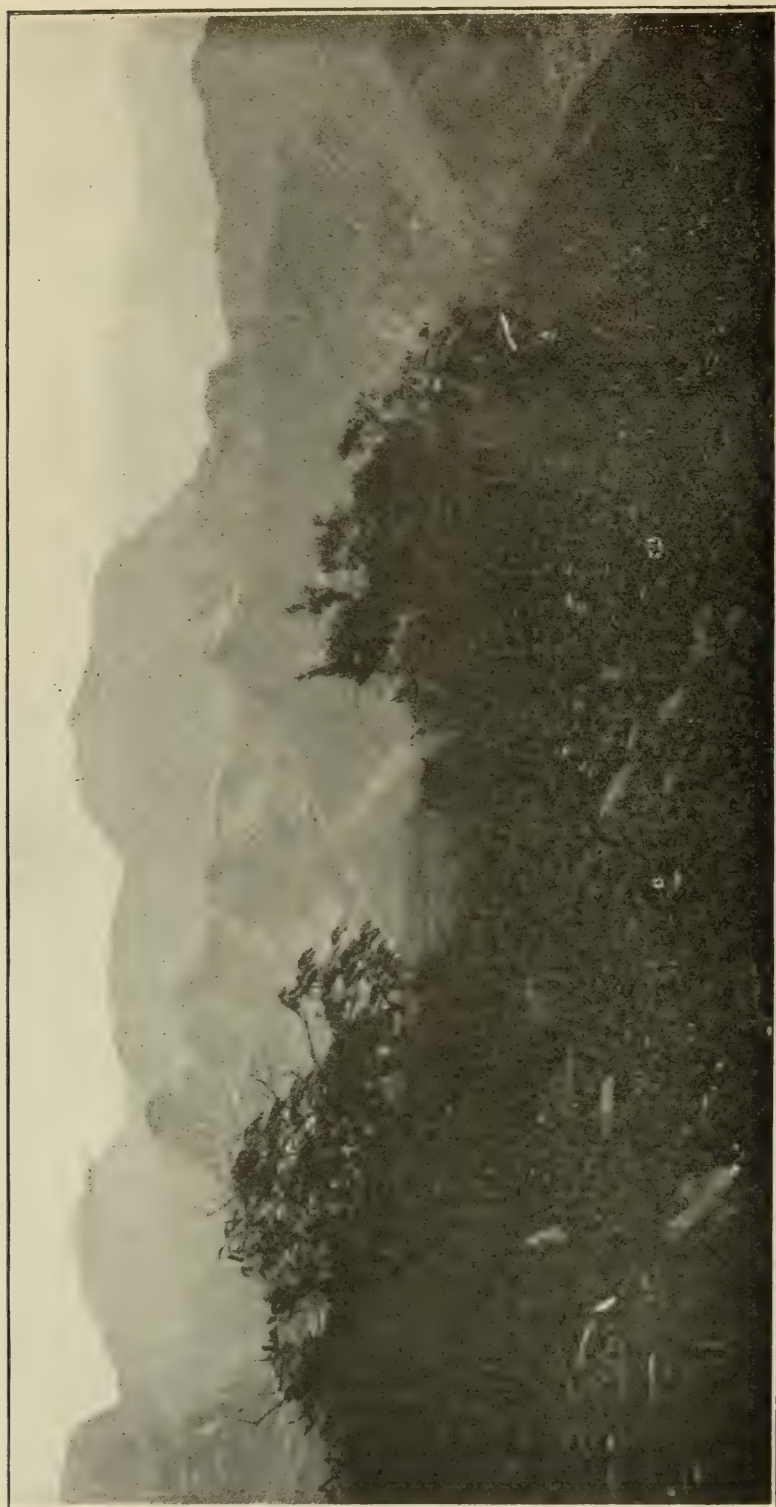


FIGURE 5.—*Cochabamba-Santa Cruz Geology*

Mature dissection of the flat-lying Bermejo sandstones and shales in the Sierra de Santa Cruz, near Bermejo, Bolivia.

two or more feet across, although most of them are less than six inches. The black shales near the base of the formation have no interbedded tillite. Interfingering with them are brown sandstones. In places the shale-sandstone contacts are very uneven, but these suggestions of unconformability are very restricted (see figure 6).

The Bermejo formation is believed to be for the most part continental in origin, although the few fragments of invertebrates observed may indicate marine or brackish water conditions. The thickness and uniformity of the beds show that it was either laid down in a basin with great marginal relief or else in a subsiding basin. The massive sandstones are almost certainly water-laid. The clays undoubtedly are, although they do not resemble marine beds and lack the fossils so commonly associated with clays deposited in the sea. The faceted pebbles scattered through both shales and sandstones indicate the presence of streams issuing from a glacier front or from glacier-capped highlands. The black basal shales are thought to owe their color to original material rather than to organic matter accumulated during their upbuilding. The conclusion tentatively reached is that the Bermejo was laid down in an interior basin, crossed by meandering rivers, with glacier-capped lands on the margins. At times the glaciers extended well into the basin, and then the coarse material which formed the tillites was deposited either directly from the melting ice or by the streams close to the edge of the ice. At other times the streams dropped their coarse material closer to the margin of the basin, and only rock dust and fine sand were carried far into the basin, where they were built into the massive clays and heavy sandstones. It is very probable that the basin was invaded by the sea from time to time, but the low temperatures induced by the waters of the ice-fed rivers probably repelled all but a few hardy forms of marine life, so that little record of them is to be expected.

CAJONES LIMESTONE

The Cajones limestone lies immediately above the Bermejo formation and is believed to be separated from it by a pronounced unconformity, although it cannot be stated positively that such unconformable contacts as were seen are not very restricted in lateral extent.

No good exposure of this formation was seen on the traverse between Cochabamba and Santa Cruz, although its outcrop was crossed, and abundant float in the streams proved its presence. Subsequent work



FIGURE 6.—*Cochabamba-Santa Cruz Geology*
Local unconformity in the basal beds of the Bermejo formation.

along the mountain front north of Santa Cruz gave details of its character and relation to the Bermejo.

The Cajones limestone comprises a series of intercalated sandstones, claystones, and limestone conglomerates that may have an aggregate thickness of 800 feet. Most of this thickness is occupied by limestone conglomerate. The pebbles are red shale, dark quartzite, red orthoclase granite, much vein quartz (which is commonly white, but may be black, brown, or rosy), and a small percentage of other rocks. The bedding is quite thin, few individual beds exceeding 20 feet in thickness (see figure 7).

This formation is thought to be the result of an invasion of the sea over the eroded, pebble-littered surface of the Bermejo formation.

SAN YSIDRO FORMATION

The San Ysidro formation was named by the writers from the settlement of San Ysidro, on the Santa Cruz Trail, about 75 miles west and 30 miles south of Santa Cruz. The westernmost exposure noted is about 14 miles west of San Ysidro, and the formation occupies the surface from that point to about eight miles east of the town, where it covers the lower flanks of a steep ridge that is capped by rocks of the Material formation.

The San Ysidro formation is believed to be Tertiary, although no paleontological evidence to support such a belief was found. The lithology and "new" appearance of the beds, their very unconformable relation to the underlying Material, and their absence between any two of the other formations described, suggesting that they post-date the Cajones limestone, which would make them at least as late as Cretaceous, are the bases for the classification.

The thickness of the formation is thought to be about 1,000 feet. It may be half that, or as much as 5,000 feet. It comprises shales, a few thin sandstones, and at least one bed that is composed chiefly of volcanic ash. The general color is light gray to white, but the thin sandstones lend contrast, as they are, almost without exception, dark red. Individual beds of shale are thin, and exposures near the trail showed neither fissility nor lamination.

The tuffaceous bed mentioned is whitish gray on both weathered and fresh surfaces. The bed would be almost pure white were it not for an admixture of tiny flakes of biotite which gives a "pepper-and-salt" appearance to a closely examined surface. Distinct bedding and imperfect ripple-marks indicate that the material was water-laid.

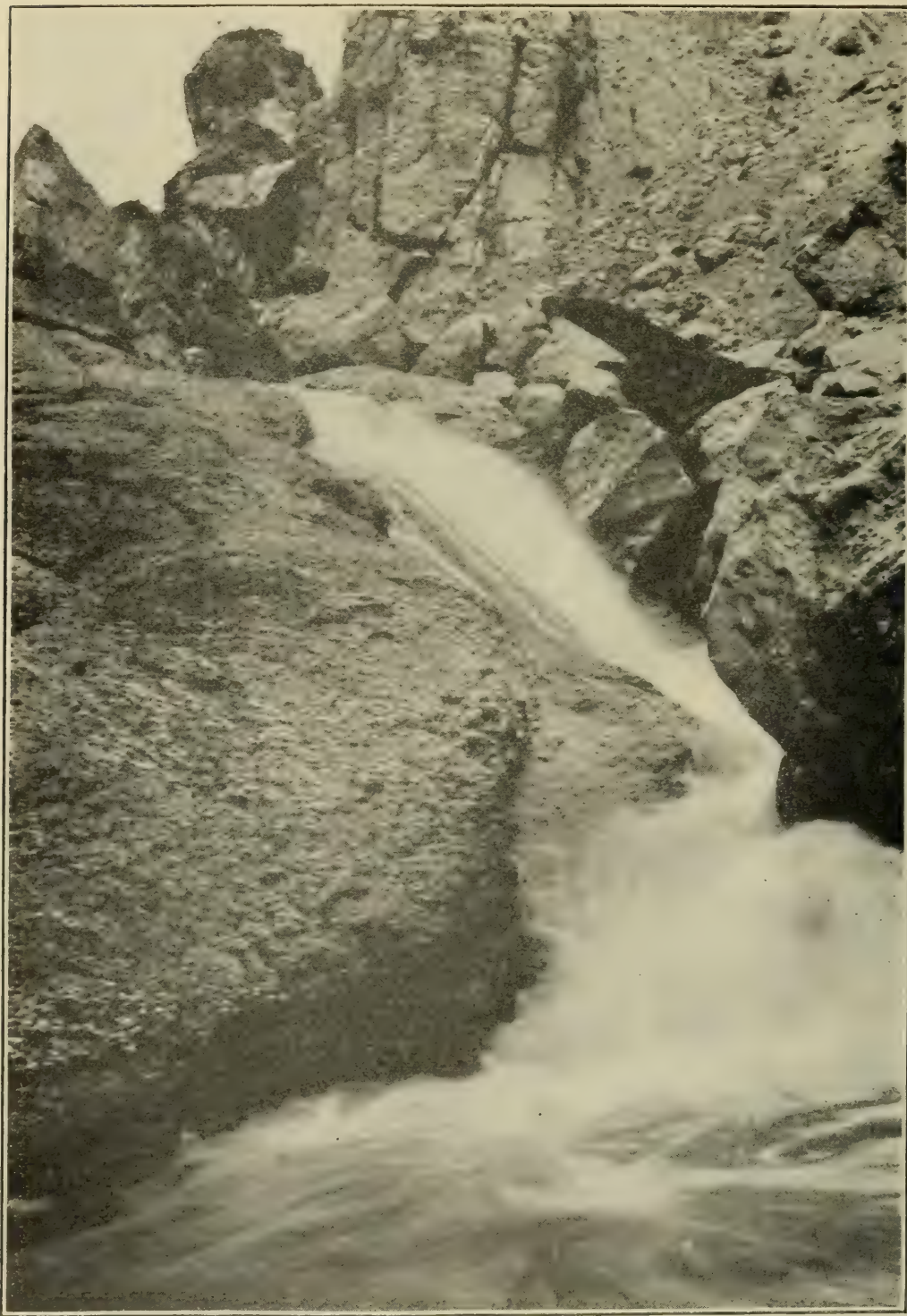


FIGURE 7.—*Cochabamba-Santa Cruz Geology*
The cascades over the Cajones limestone in the Espejos quebrada.

The general appearance of this formation suggests the Oligocene beds of eastern Wyoming more than any other formation with which the authors are familiar. It was probably built up by sluggish streams, along whose courses there may have been shallow lakes. The surface covered by them is thought to have had considerable relief, which was gradually buried. This could be accomplished by the filling action of wide, shallow, mud-laden rivers, in much the same manner as the work done by the Arkansas and other streams that flow through the Great Plains.

QUATERNARY

The trail crosses no consolidated rocks between a point 22 miles south and 18 miles west of Santa Cruz and the city itself. The surface is occupied by gravels, sands, and clays, which extend to an unknown but comparatively shallow depth. The gravels are for the most part hard fragments from the Totora and Bermejo formations, with some of the faceted pebbles of the tillite beds. The sands fall into two classes—river sands and dune sands. The only difference between the two is in mode of transportation, for the individual grains migrate from one class to the other. These sands are almost pure quartz and probably come principally from the sandstones of the Bermejo formation. The dune sands cover most of the plains around Santa Cruz. In places they form low hummocks and curved ridges, which are now anchored in place by a growth of stunted timber and long grass. Live, migrating dunes are rare.

The clays cover only a small part of the surface. They are commonly dark brown in color, but some of them have more than a hint of redness, suggesting that they are outcrops of the red clays that, farther to the east, north, and south, surface much of the plains.

STRUCTURE

Throughout most of the area traversed the rocks have been subjected to strong lateral stress and have yielded to it by folding and breaking, so that they are commonly steeply tilted and their continuity is broken by many faults. The most intense deformation is not in the westernmost beds, as might be anticipated if the deforming stress was a thrust from the west, but rather about midway between Cochabamba and Santa Cruz. Near Arani, on the west, the beds are only gently flexed and indicate a force acting from the southwest rather than from the west.

This same direction of stress seems to hold in the more intensely deformed areas. On the east front of the mountains the Bermejo sandstones form well-defined hogbacks, or *cuestas*, whose back slopes dip eastward with angles of 20 degrees or less until they disappear beneath the Quaternary deposits of the Santa Cruz plains.

TRENTON OF CENTRAL TENNESSEE AND KENTUCKY¹

BY PERCY E. RAYMOND

(Presented before the Society December 28, 1921)

CONTENTS

	Page
Introduction.....	571
The section in Kentucky.....	571
Correlation.....	573
The section in central Tennessee.....	574
The section at Nashville.....	575
Correlation with Kentucky.....	578
The Cynthiana, Catheys, and Leipers.....	579
Summary.....	583
Correlation table.....	585

INTRODUCTION

The correlation of the Trenton strata of the central portions of the States of Tennessee and Kentucky with the deposits of the same age in other regions has been accomplished in a general way, but there is considerable difference of opinion as to the equivalence of the subdivisions. Through the aid of a grant from the income of the Shaler Memorial fund at Harvard University, I was able to spend two weeks on this problem, and as a result have come to look upon it in a way somewhat at variance from any solution I have seen in print and also from my own preconceptions, obtained from the study of the literature.

I am greatly indebted to Mr. Wilbur A. Nelson, the State Geologist, for much assistance in Tennessee, and to Prof. Arthur M. Miller for similar courtesies in Kentucky.

THE SECTION IN KENTUCKY

The work of Professors A. M. Miller and August F. Foerste in the "Blue Grass" region of Kentucky has amply elucidated the stratigraphy and paleontology of the Ordovician formations of that area. An idea of

¹ Manuscript received by the Secretary of the Society January 31, 1922.

the succession may be well obtained from Professor Miller's Report on the Georgetown Quadrangle,² with certain nomenclatorial modifications set forth by him in his later report (1919) on the Geology of Kentucky.

The lower Maysville (Mount Hope) is believed by Foerste to be represented in the upper part of the Garrard sandstone, which is really a siliceous limestone. The Eden, which does not seem to be readily subdivided, is called the Million shale, and consists of thinly bedded limestone and marlite, with a thickness of 120 to 200 feet. At the base, thin layers of limestone contain *Cryptolithus tessellatus*, *Plectambonites rugosus*, and an abundance of columnals of crinoids.

The Cynthiana consists of thinly bedded blue limestone which weathers to a rubbly mass and contains numerous fossils, *Cyclonema varicosum* being considered most characteristic. The thickness is about 35 to 60 feet in central Kentucky, but increases northward, where the 50 feet of Point Pleasant beds on the Ohio River raise the total thickness to 100 feet. The lower and more widespread part is known as the Greendale.

Beneath the Cynthiana is the Lexington series, the upper member of which varies from place to place. On the northern and eastern sides of the basin the Cynthiana rests upon the Woodburn, but on the west there intervenes the Perryville, which may have from one to three members. These are, in descending order, the Cornishville, the Salvisa, and the Faulconer. The Cornishville appears to be a very local bed, found only in Mercer County, and contains the same fauna as the Benson. It is only 5 feet thick. Beneath is the Salvisa, a "birdseye" limestone, dense, buff, weathering white, and containing *Tetradium* and ostracods. The thickness varies from 0 to 15 feet. At the base is the Faulconer, which is often a single bed 5 to 8 feet in thickness, made up of shells of gastropods. As stated above, these formations occur on the southwestern flank of the arch and drop out in descending order northward, so that the Cynthiana rests in places upon the Salvisa, in others upon the Faulconer, and more generally upon the Woodburn. The interpretation of this condition may be discussed later.

The Woodburn is a highly phosphatic limestone with rather numerous fossils. It is 50 to 60 feet in thickness and differs faunally from the Benson in the presence of *Columnaria alveolata*.

The Brannon beneath is merely a useful horizon-marker, its limestone being siliceous and furnishing chert on weathering. It is 7 to 10 feet thick, with few fossils, but often shows a contorted layer which suggests the effect of subaquatic slumping.

² Kentucky Geol. Survey, ser. 4, vol. 1, pt. 1, 1913, p. 317.

The Benson is a thinly bedded limestone, about 35 feet thick, with *Dinorthis ulrichi*, *Strophomena vicina*, and a layer of *Stromatocerium* in its upper portion. It is not separated very sharply, either faunally or lithologically, from the Jessamine below.

The latter formation, about 70 feet thick, consists of thinly bedded limestone with rather thick shaly partings, and is the zone of *Prasopora simulatrix*. It also contains many of the common Trenton fossils, such as *Zygospira*, *Plectambonites*, and *Dalmanella*. It shares with the other subdivisions of the Lexington the brachiopods *Hebertella frankfortensis* and *Rhynchotrema increbescens* and seemingly lacks any representative of the genus *Platystrophia*.

Beneath is the Logana, 25 to 35 feet in thickness, made up of somewhat clayey limestone and shale, the characteristic fossil being the exceedingly rare *Heterorthis clytie*. What is more significant, this formation occasionally furnishes *Cryptolithus tessellatus*, which I was fortunate enough to find at this horizon in the section at the Old Crow distillery, on Glenss Creek, and which Foerste has previously listed, although without locality.³

The lowest bed of the Trenton succession, the Curdsville, is rather sharply set off from the Logana above as a massive, coarsely granular, gray limestone about 10 to 12 feet in thickness. It in turn rests upon the Tyrone with a "welded" contact. The upper layers of the older formation show shrinkage cracks, indicating emergence after their deposition.

CORRELATION

Aside from its exotic series of Echinoderms, which have no great value in correlation, the fossils of the Curdsville ally it closely to the Leray of New York, with which it has sometimes been correlated. Such species are *Receptaculites occidentalis*, *Streptelasma profundum*, *Columnaria halli*, *Orthis tricenaria*, and a large fauna of mollusca. This summer, however, I found a number of specimens of a *Platystrophia* which is probably the form called *P. trentonensis* by McEwan. This indicates a somewhat mixed Trenton and Leray fauna, such as is found in the Rockland in Ontario.⁴

The presence of *Cryptolithus tessellatus*, *Dalmanella*, and *Mesotrypa quebecensis* in the Logana, together with its relation to the Jessamine above, is sufficient to correlate the formation in a general way with the

³ Kentucky Geol. Survey, ser. 4, vol. 1, pt. 1, 1913, p. 372.

⁴ A. E. Wilson: Dept. Mines Canada, Bull. 33, 1921, p. 19 et seq.

P. E. Raymond: Geol. Survey Canada, Sum. Rept., 1912, p. 399.

Glens Falls of New York. The Jessamine is comparable to the familiar Prasopora beds of New York and Ontario. Numerous differences between the two could be pointed out, such as the abundance in Kentucky of *Rhynchotrema increbescens* and *Hebertella frankfortensis*, the rarity of trilobites, and absence of such guide fossils as *Triplecia*, *Trematis*, and *Parastrophia*; but there are, perhaps, as many similarities as could be expected, taking into consideration the geographical situation.

With the Benson, *Platystrophia* reenters, and it may or may not be significant that representatives of this genus are very rare in the lower 175 feet of the Trenton at Trenton Falls, New York.

The Woodburn is marked by the appearance of *Columnaria* for the first time above the Curdsville, but otherwise its fauna shows nothing remarkable. The whole series to this point, with a thickness of about 200 feet, is fairly closely comparable to, and to be correlated with, the lower 226 feet of the composite section of the Trenton at Trenton Falls and on Rathbone Brook, New York.⁵ This is practically the conclusion which I reached in 1916, but which opinion has been strengthened on seeing the exposures in the field.

Before discussing the correlation of the Perryville and higher strata, it is well to review the situation in Tennessee.

THE SECTION IN CENTRAL TENNESSEE

The basis of modern knowledge of the Trenton of the Nashville dome is the work of Ulrich, published in best form by Hayes and Ulrich in the Columbia folio of the U. S. Geological Atlas, 1903.

In this region the highest Ordovician formation is generally either the Fernvale (Richmond) or Leipers (Maysville) and the present practice is to consider the Catheys as the highest formation of the Trenton. The following section, given in descending order, will, however, include the Leipers:

Leipers.—Granular blue limestone, sometimes earthy, knotty, and shaly; very fossiliferous. Thickness, 0-100 or more feet.

Catheys.—Thinly bedded, fine grained earthy and shaly limestone with numerous fossils. Thickness, from 50 to 120 feet.

Bigby.—In the typical region, which is in the vicinity of Columbia, this is a granular, crystalline, phosphatic limestone, without shale except locally at top or bottom. Thickness, 50 to 150 feet.

Hermitage.—Thinly and thickly bedded limestone with some shale. Thickness, 40 to 70 feet.

⁵ Raymond: Bull. Mus. Comp. Zool., vol. 56, no. 3, 1916, p. 253.

The Hermitage rests upon the Carters, which is generally, although perhaps not everywhere, of Leray-Black River age.

Having enumerated these formations, beginning with the youngest, they may be best considered in reverse order.

The Hermitage is chiefly remarkable for the extraordinary abundance of specimens of *Dalmanella fertilis* Bassler, a shell which in many places occupies the layers to the exclusion of all other fossils. It is, in fact, the guide fossil, and it is the usual practice to place the top of the Hermitage at the horizon where this brachiopod ceases to be abundant. Curiously, even it is not common in Rutherford County, where the lower 50 to 70 feet of the Trenton are nearly unfossiliferous.⁶

The Bigby is an exceedingly interesting formation, with a highly diversified development in various parts of the central basin. Its characteristics in the typical region have been mentioned above. In Davidson, Franklin, and more eastern counties it is chiefly remarkable for the development it shows of the so-called "Bigby Dove" or "Upper Dove" strata. These consist of thickly bedded, pure, fine grained buff limestone which greatly resembles the Lowville or "Birdseye" and which contains an abundance of Tetradium and Ostracoda along with some other fossils, chiefly mollusca. At Nashville these beds are not thick, but farther eastward they become the Cannon formation of Ulrich⁷ and reach a considerable thickness. About this development almost nothing has, however, been published. According to Ulrich,⁸ the thickness of the Bigby between Hartsville and Carthage (in the northeastern part of the basin) is between 120 and 150 feet and more than half of it is "dove." The fauna, moreover, while profuse, is mostly molluscan, bryozoa and brachiopods being almost absent.

The discussion can, perhaps, be made more concrete by reviewing the well known section at Nashville. The following measurements were made by the writer in 1921, and for convenience in reading are given in ascending order.

THE SECTION AT NASHVILLE

The lowest layers of the Trenton are most conveniently studied in the cuttings along the Nashville, Chattanooga, and Saint Louis Railroad in the southeastern part of the city. The Hermitage rests here upon the rather thinly bedded upper layers of the Carters.

⁶ Galloway: Tenn. Geol. Survey, Bull. 22, 1919, p. 51.

⁷ Bull. Geol. Soc. Am., vol. 22, 1911, p. 417.

⁸ Columbia folio, 1903, p. 2.

1. Thinly bedded limestone, full of *Dalmanella*, with partings of unfossiliferous shale—20 feet.
2. A layer of much contorted limestone and shale. The original mass seems to have been well stratified, the limestone in beds 2 to 6 inches thick. As a result of pressure, the layers have been disrupted, folded, tilted, and even rolled over, forming boulder or pillow-shaped masses. The appearance is that of a deposit which has slid while still relatively soft, rather than that of a series which has been folded after consolidation—3 feet.
3. Limestone in thick layers, almost entirely made up of shells—8 feet.

By continuing to a cutting on the next railroad west of this, and thence to Fort Negley, it is possible to get a fair idea of the succession to the top of the Catheys, but the section is exposed in greater detail along the Tennessee Central Railroad between the City Hospital and the Cumberland River. It was not possible to connect the section above definitely with what follows, but it is probably all below number 4.

4. Impure limestone, some layers made up chiefly of *Dalmanella*; 18 inches of shaly limestone at top—7 feet 6 inches.
5. Irregularly bedded light gray limestone with thin partings of shale. *Dalmanella* common, some bryozoa present—17 feet.

Top of the Hermitage.

6. Light gray, coarsely granular, cross-bedded limestone, in layers 1 to 6 feet in thickness. The cross-bedding is well brought out on the surfaces and edges of the layers by the large amount of phosphate present. Few complete, but many fragmentary fossils are to be found. The highest layer contains flat pebbles of limestone, usually about half inch in thickness and from 2 to 6 inches in greatest diameter. There are also larger fragments of stratified limestone up to 8 inches in thickness and 16 inches in length. Scattered about among the pebbles are mutilated shells of pelecypods and cephalopods. This is the Capitol limestone of Safford and it is evidently, as he stated, a deposit of calcareous sand. Its bedding indicates wave action, and very shallow water, if not actual emergent conditions—28 feet.
7. Pure, buff limestone full of small calcite-filled "tubes." The "birdseye"-like layers are interbedded with less pure limestone. The upper foot is somewhat shaly and contains a great abundance of ostracods—7½ feet.
8. Dark gray, impure limestone with a layer almost entirely made up of a large massive *Tetradium* at the top—4 feet.
9. One layer of the pure buff limestone filled with *Tetradium racemosum*—1 foot.

Zones 7 to 9 make up the so-called "Bigby Dove," which has already been commented upon. Aside from ostracods and *Tetradium*, it contains few fossils, those seen being gastropods. In former times this fine-grained pure limestone would have been considered indicative of deep-sea

conditions, but south of Franklin I saw a large surface of one of the pure layers which exhibited deep shrinkage cracks, forming a pattern of large polygons. The more probable interpretation is, therefore, that these beds are the deposits of lagoons, which were so shallow that at times they were entirely deprived of water and exposed to desiccation. Taking these strata and the Capitol limestone below them, they together suggest conditions which obtain at the present time about reefs in the tropical seas.

10. Massive gray limestone with nodules and extensive lenticular layers of chert—26 feet. This is the Ward limestone of Jones.
11. Thinly bedded gray to buff limestone, which rests unconformably on the layers below and is itself truncated by the strata above—4 feet.
12. Pure buff limestone, which increases from a layer of nodules in the western part of its exposure to two beds, each about 1 foot thick, at the eastern—0.2 feet.

Zones 11 and 12 appear to represent beds formed just at the margin of a lagoon, and that they cut across the strata beneath has only a limited significance till it can be determined how much has been cut out.

Safford (Geology of Tennessee, page 277) called attention to these two zones, which have a variable thickness in the rather numerous exposures about Nashville. Number 11 he called the *Cyrtodonta* bed and stated that in the bluff at the wire bridge it was a single bed, 10 or 11 feet thick, made up of the shells of *Cyrtodonta saffordi*, *Bellerophon lindsleyi*, and *B. troosti*.

"The bed is seen at the engine-house of the water-works, where it is 6 feet thick. In tracing it beyond the engine-house it very soon runs out and is replaced by a compact dove-colored limestone."

Paul M. Jones, in a little-known paper,⁹ which I have seen through the courtesy of Mr. W. A. Nelson, has described in some detail the characteristics and distribution of the *Cyrtodonta* bed and the "Upper" or "False Dove." The former is stated to be a very local development, occupying only a small area near Nashville. It varies in thickness from 0 to 11 feet, and is usually a single bed, made up of an aggregation of molluscan shells. The "False Dove" is from 2 to 5 feet thick, and contains ostracods, gastropods, and cephalopods, with an occasional *Tetradium*. Although it has, on the weathered surface, much the same appearance as the "Bigby Dove," it is really a much less pure and less compact limestone.

13. Massive limestone with numerous bryozoa, succeeded by rather shaly strata. Base of the Catheys—17 feet.

⁹ The geology of Nashville and immediate vicinity. Nashville, 1892.

14. Rather thinly bedded strata which weather to a rubbly mass—30 feet.
15. Less shaly beds with a layer of large *Stromatoceria* and *Columnaria* at the base—12 feet.
16. A layer of much contorted limestone suggesting slumping. Rolled effect particularly well shown—10 inches.
17. Limestone like 13—7 feet. This is the highest exposure near the station of the Tennessee Central Railroad.

CORRELATION WITH KENTUCKY

About 7 feet above the base of zone 13 one finds the typical Catheys fossils, such as *Cyclonema varicosum* and *Constellaria emaciata*; so that a part at least of the Catheys is to be considered as of the same age as the Cynthiana. The layer of *Stromatocerium* at the base of number 15 is probably not the "Sponge bed" of Jones' paper, since it lies 37 feet above the "False Dove." Jones stated that the Sponge bed rested in some places directly on the False Dove, whereas in others it was separated from it by from 10 to 15 feet of ordinary blue limestone.¹⁰ He mentioned another occurrence of *Stromatocerium* as much as 25 feet above the Sponge bed, and it is probable that it is this higher layer which was encountered in the above section. Jones attached considerable importance to the Sponge bed, considering its top the upper limit of the Trenton. If there is more than one such stratum, as there apparently is, a bed of *Stromatocerium* will prove a very unreliable indicator of the plane of separation of two formations.

The abundance of *Bellerophon troosti* and other gastropods in the Cyrtodonta bed (number 11), and particularly its association with a "Birdseye" limestone (number 12), justify its correlation with the Faulconer, and the False Dove with the Salvisa, these two representing the Perryville. Whether or not the lower part of number 13 is the Cornishville has not been determined.

The Ward limestone is, according to Jones, fairly fossiliferous, and it is significant that in it is the lowest horizon at which *Columnaria alveolata* is found. He also lists *Orthis borealis* (*Hebertella frankfortensis*) and *Rhynchonella fringilla* (probably *Orthorhynchula linneyi*). These fossils strongly suggest a correlation with the Woodburn of Kentucky. It may also be noted that these are the only strata in the section which produce chert, and since that is a unique characteristic of the Brannon in Kentucky it is entirely possible that the Ward represents both the Brannon and the Woodburn. At Columbia, according to Hayes and Ulrich,

¹⁰ Loc. cit., p. 45.

the top of the Bigby is a finely granular, siliceous rock, which also suggests the Brannon bed.

Writers upon the Trenton of these States seem to be in general agreement that the Hermitage of Tennessee is equivalent to the Logana of Kentucky, this opinion being based almost entirely upon the fact that *Dalmanellæ* are exceedingly abundant in both. This would be a harmless enough correlation if it were not followed by the logical deduction that the Jessamine is not represented in central Tennessee.

The lower strata at Nashville contain almost nothing except the *Dalmanella* to which Bassler has given the name *fertilis*. In the vicinity of Columbia, Tennessee, Hayes and Ulrich list a small fauna in which *Prasopora patera* is said to be abundant and *P. simulatrix* common. Miller states that in Kentucky he separates the Jessamine from the Logana because only in the former do *Prasopora simulatrix* and *Dalmanella* occur together. In the Jessamine, *Dalmanellæ* are equally as abundant as in the Logana, and it is only at the base of the Benson that they disappear. Like the Capitol limestone above it, only to a lesser degree, the Hermitage is irregularly bedded, and in places the strata are nothing more than masses of wave-piled shells. How long a time is represented by the Hermitage and Bigby together can not be determined from the formations in the area which I studied, but I should judge that deposition began only in the later part of Jessamine time. The particular fossils characteristic of the Benson have not been found in the Bigby, but that is hardly surprising, considering the conditions under which the latter appears to have been deposited. Of the various fossils listed from the Bigby of Tennessee by Hayes and Ulrich, *Constellaria teres* appears in Kentucky first in the Woodburn, while *Hebertella frankfortensis*, *Rhynchotrema increbescens*, and *Cyrtolites retrorsus* are found in the Jessamine and higher strata.

THE CYNTHIANA, CATHEYS, AND LEIPERS

If now attention be turned to the upper part of the section, more difficulties will be encountered. They are, however, difficulties which we have fabricated for ourselves by our habits of thinking rather than any presented by the strata and faunas themselves. Dr. Ulrich holds that the Catheys and Cynthiana are to be classed with the Trenton, while Professor Miller would unite them with the Cincinnati. All who have written on the subject agree that the "Utica" and Eden are absent from Tennessee, and that the Leipers is of Maysville age.

In such regions as the vicinity of Nashville and the southwestern part

of the Blue Grass area in Kentucky, where the Perryville intervenes between the Woodburn and Catheys, the Trenton succession is obviously broken, and at about this place new elements enter the fauna and some of the old ones disappear. One of the most striking things noted is a sort of quickening of evolutionary processes, as though the species had long been dormant and now began to change. This is seen especially in certain of the brachiopods. The *Platystrophias* of the Curdsville, Hermitage, Bigby, Benson, and Woodburn are all small things, more or less alike, but in both the Catheys and Cynthiana they increase in size, till at the top some specimens are nearly as large as any in the later Ordovician. The little *Hebertella frankfortensis* is replaced by *H. maria parkensis*, some specimens of which can hardly be distinguished from *H. sinuata*. *Rhynchotrema increbescens* gives way to *Orthorhynchula linneyi*, which, starting in the Salvisa with a small form, increases in size throughout the Cynthiana, Catheys, and Leipers.

As compared with deposits in New York and Ontario, there is absolutely nothing in common which has any weight in correlation. This is explained by the fact that the Upper Trenton was a time of uplift and deposition of shale in New York. Kentucky and Tennessee also felt the effects of uplift at this time, as already shown, but they were too far from the land to be affected at first by the clastic material which destroyed much of the Trenton fauna in New York and brought about the "Utica" facies. The uplift which affected that part of Kentucky occupied by deposits of the Perryville seems to have been followed by a slight deepening of the waters during Cynthiana times, so that lagoon conditions were replaced by those of shallow seas or banks on which corals, bryozoa, and brachiopods flourished.

The general effect of the uplift at the east had been to bring the shores appreciably nearer this region and may have diverted to it currents carrying an augmented food supply, thus causing the "awakening" referred to above. These more favorable conditions did not persist long in Kentucky, however. The mud of the Utica came as near as the Ohio River (Fulton shale) and drove out or killed the Trenton—Cynthiana fauna there. In the section on Glenn Creek at the Old Crow distillery, the bed which shows the second appearance of *Cryptolithus* is only about 35 feet above the base of the Cynthiana, and with the coming of that trilobite the warm water fauna (Cynthiana) disappears from the region. Then follows a long period (Million shale) when there was mud in Central Kentucky and the fauna was much reduced in variety.

If one turns now to Tennessee, one finds the Catheys much thicker than the Cynthiana, and, furthermore, the Cynthiana-Catheys fauna per-

sists in the strata which are assigned to the Leipers. There are not many species which pass from the Catheys to the Leipers, but the faunas are essentially alike, the younger being a derivative of the older, and in actual field-work it is very difficult to distinguish the two.

This is especially well illustrated in the section in the city of Nashville. The highest strata, well exposed in a large quarry north of the reservoir and at Fort Negley, on the summit of Saint Cloud hill, are called Catheys by some and Leipers by others. And verily these beds carry a mixed fauna. Large specimens of *Orthorhynchula linneyi* are very common there, and a variety of *Platystrophia ponderosa*, much larger than any of the specimens lower in the Catheys, is not infrequent. On the other hand, large *Isochilinæ* and *Cyclonema varicosum* proclaim the Catheys, while *Hebertella sinuata* provides but indifferent evidence.

There is, furthermore, no physical evidence so far brought forward which indicates any interruption of sedimentation at the top of the Catheys. The clearest statement on the part of one who believes that there was a land interval between the Catheys and Leipers is that of Ulrich.¹¹

"In middle Tennessee, where the emergence at the close of the Trenton continued through Utica and later stages of the Eden the elevation must have been very broad and without marked local flexing. Erosion of the Catheys prior to the submergence of the west and north flanks of the dome by the late Cincinnati or Leipers sea is indicated chiefly by the local absence of some of the upper layers. There are no elastic deposits worth mentioning at the contact of the Leipers and Catheys. The plainest feature of the physical evidence of the hiatus between the two is the unquestionable landward overlap of the Leipers. The most western exposures of the contact contain a number of clearly distinguishable beds in the lower part of the Leipers which are entirely absent in the Nashville hills; and on the south flank, as near Fayetteville, the Leipers is represented by only the uppermost member, the lower *Platystrophia* bed."

The evidence for the overlap mentioned is outlined in the Columbia folio, and consists in the fact that different faunas were found in the strata considered to be the base of the Leipers at different localities. This does not seem to the writer at all sufficient to establish the case unless accompanied by a very detailed explanation of the distribution of the various species.

In place of the current opinion that Catheys and Leipers times are separated by an interval during which the Eden of Kentucky and Ohio were deposited, I wish to present the idea that this was a region of con-

¹¹ Bull. Geol. Soc. Am., vol. 22, 1911, p. 311.

tinuous deposition, unaffected by the conditions which introduced the mud into the more northern Eden, and that it was the region in which the Maysville fauna originated and from which it spread northward at the end of Leipers time.

If this contention can ultimately be established, as I do not pretend to do more than suggest the idea now, then central Tennessee was one of those districts to which animals retired when driven from their earlier environment by physical changes and from which they emerged to repopulate later seas. It was, in fact, an asylum for a recurrent fauna. Dr. Ulrich has already commented upon the Catheys fauna as of the recurrent type, and called attention to the fact that it really is a combination of two faunules, one consisting of corals and hydrocorallines (*Strepelasma*, *Tetradium*, *Columnaria*, and *Stromatocerium*) and the other of bryozoa and shells.¹² It should be noted that in the correlation of the Leipers fauna with that of the Fairmount the first of these elements has to be neglected, and this seems a very important point. If the Leipers received its fauna from the Catheys, the presence of numerous corals is readily understood. The real Fairmount could not have supplied them.

The coral faunule, so far as *Columnaria* and *Tetradium* are concerned, is autochthonous in Tennessee. These genera occur in various subdivisions of the Stones River as high as the Carters, then disappear from the central basin during the Hermitage and Bigby, although I have no doubt that they are in the Cannon (*Tetradium* is present in the "Bigby Dove"), reappear in the Catheys and Leipers, and thence pass into the Arnheim, and so to the Richmond. Although not yet proven present in every formation and necessarily migrants during the uplift at the end of the Lowville or Leray, these corals seem to have had their distributional center in this area.

To summarize what has been said above, it is argued that the Catheys and Leipers are the equivalent of the Cynthiana, Million, and Lower Maysville in Kentucky and the Upper Trenton, Eden, and Lower Maysville about Cincinnati, because:

1. Lithologically, there appears to have been continuous sedimentation throughout Catheys and Leipers time.
2. The fauna of the Leipers is a derivative of that of the Catheys.
3. Certain of the species of the Catheys show a direct evolution into the species found in the Leipers.
4. The Leipers is not a pure Maysville fauna, but contains elements indigenous to the region it occupies. It was, therefore, emigrant and not immigrant.

5. There is no evidence anywhere of emergence previous to, during, or at the end of "Utica" time. There is ample evidence that Utica is a facies of sedimentation and not a time division. It represented off-lap deposits which progressed westward, but never reached central Tennessee. On this subject there is a considerable literature by Grabau, Ruedemann, and the writer, and it does not require repetition.

SUMMARY

All of the discussion in this paper must be understood as an attempt to interpret the meaning of certain sediments and faunas. Others are much more familiar with the areas in question than I am, and much work has been done that never has been published. I have attempted to show that physical conditions were very different in Tennessee from those which obtained in Kentucky or other areas nearer the shore, and that the faunas must be interpreted in the light of those conditions. It is very easy to make correlations based on similarities or differences of fossils alone, especially if one can warp the crust of the earth about at will, bring in or abolish seas, and bring faunas ready made to the areas where they were entombed. To actually unravel all the tangled skeins of mixed faunas, evaluate earth movements which brought about only limited emergences, and correlate the unlike faunas of the various facies of the same sea is a more complex problem and will take more facts and longer time for its solution.

The rocks which make up the Hermitage and Bigby of central Tennessee show the physical characteristics of shallow-water deposits. The coarsely crystalline, cross-bedded strata of the Hermitage and Capitol appear to have been formed near a low, reef-barred shore or coral island, and the "dove" may be interpreted as having been deposited in shallow pools or lagoons. Both the "Bigby dove" and the Perryville dove (*Salvisa*) truncate the strata below, the whole series indicates intermittent sedimentation, and it is possible to evaluate the element of time only approximately. Until the Perryville, conditions seem to have been more quiet and normal in Kentucky, and the section in Tennessee must be measured by that standard.

There seem to be two possible interpretations of the Perryville, and both involve uplift nearly or quite to emergence at the end of the Woodburn or the Perryville. Although, as indicated above, this formation is generally confined to the southwestern flank of the Cincinnati dome, Professor Miller¹³ has found an exposure on the southeastern side near

¹³ Second Ann. Rept. Kentucky Geol. Survey, ser. 4, vol. 2, 1914, p. 32.

Paris, Kentucky, and surmises that it once passed all across the southern part of the arch and has subsequently been removed. This would involve uplift and erosion after the Cornishville and before the Cynthiana.

If, however, the Salvisa be the deposit of a lagoon, it would involve only a shallowing of the water at the end of the Woodburn and sufficient uplift or upgrowth that basins might be formed. In that case the deposit about Paris may not have been connected with the greater one south of Frankfort.

Lithologically, the Faulconer is a mass of shells such as would be most apt to occur near a shore or on a bank or reef. Furthermore, the transition between the Woodburn and Cynthiana, where there is no Perryville present, is a gradual one, and it is practically impossible to draw a line between the two on lithological grounds. Faunally, the Cornishville above the Salvisa is allied with the Benson and Woodburn rather than the Cynthiana, but the Woodburn and Salvisa contain the earliest of the Cynthiana types. Everything, therefore, suggests a very brief "lost interval" at this horizon.

The very great difference between the fauna of the Upper Trenton in Kentucky and that of northern New York, Ontario, and Minnesota must be ascribed to geographical conditions. While certain forms were migrants, others remained in or near their "center of distribution." The sea was so fully populated in later Trenton times that the animals which were driven westward by the invasion of mud found but inhospitable reception. It may also be noted that the tongue of mud which reached Cincinnati was thrust out into the Trenton sea in such a way as to make a northern and southern province, Ottawa on the north and the Cumberland front in Tennessee on the south, being far to the east of its most westward distribution. In fact, so far as we know from any actual outcrops at the present time, this mud may have formed a complete barrier to migration of shore-inhabiting animals between northern and southern seas in late Trenton and post-Trenton times.

The proper application of the term Trenton remains to be cleared up, and the discussion of the subject is best deferred until the publication of Dr. Ruedemann's studies of the Utica and Frankfort shales. It is quite patent, however, that we in America must eventually follow the Europeans in eliminating from our time-table any periods which have been based entirely upon the black shale facies. At the present time, as a matter of convenience, I am using Trenton to include deposits dating from the time of the first appearance of *Platystrophia*, which is usually immediately anterior to the first appearance of *Cryptolithus*, to and in-

cluding the zone of the second arrival of *Cryptolithus*. The following table will express my present opinion of the correlation of a part of the Ordovician strata. It should be said by way of explanation that Cobourg¹⁴ had to be substituted for the Picton of previous papers because of the preoccupation of the latter term, and that the name Gloucester¹⁵ was proposed for the "Utica" black shale of Ontario which overlies the Collingwood black shale and limestone. Neither term is new here.

CORRELATION TABLE

Central Tennessee	Central Kentucky	Ontario	Central New York
Leipers	Fairmont Mount Hope	Lorraine (part)	
	Million	Gloucester Collingwood	Frankfort Utica
Catheys	Cynthiana	Cobourg	
Perryville		Lower Cobourg	
Bigby Ward Dove Capitol Hermitage	Woodburn Brannon Benson Jessamine	Prasopora beds Typical Trenton	
Wanting	Logana	Hull	Glens Falls
	Curdsville	Rockland	Amsterdam
General emergence			
Carters	Wanting	Leray	
	Tyrone	Lowville	

¹⁴ Canada Dept. Mines, Geological Survey, Mus. Bull. no. 31, 1921, p. 1.
¹⁵ Bull. Mus. Comp. Zool., vol. 56, no. 3, 1916, p. 255.

PENEPLAINS AND THE GEOGRAPHICAL CYCLE¹

BY W. M. DAVIS

(Presented before the Society December 29, 1921)

CONTENTS

	Page
General features of a peneplain.....	587
Subsequent streams and valleys.....	589
The geographical cycle and its complications.....	590
Climatic changes during a cycle of erosion.....	591
Misconception of the geographical cycle as a rigid scheme.....	593
Essential features of the geographical cycle.....	594
Induction and deduction in the scheme of the cycle.....	595
Deduction in the scheme of the arid cycle.....	596
Unlike use of the cycle in geology and geography.....	597

GENERAL FEATURES OF A PENEPLAIN

If a landmass of whatever structure and large area be upheaved unequally to considerable altitudes in its interior area and if it then stand still for an indefinitely long period, it will be eventually degraded to a plain. In order to avoid the necessity of assuming so indefinitely long a period of still-stand, and in order at the same time to detain attention upon the gently undulating surface that such a region will have before it is worn down to a plain, the term peneplain was invented some thirty years ago. As no one, I believe, proposes to call the surface of ultimate degradation a "plane," I see no sufficient reason for calling the penultimate surface a "peneplane," as some have proposed; the original spelling, peneplain, is preferred.

When the term was first proposed it was vaguely defined; and it has recently come to my knowledge that the vagueness of its definition has led some students of the physiographic evolution of the Appalachians to make for themselves a fuller definition, which I hope they will publish. In the meantime the following statement is offered of my own views upon the subject, as they have been gradually developed during the

¹ Manuscript received by the Secretary of the Society January 24, 1922.

growth of the many ideas that are compactly embodied in the scheme of the cycle of erosion or the geographical cycle.

A peneplain developed on a large landmass of homogeneous structure should be margined along its retrograding ocean shore by sealevel delta-free valley plains, alternating with low, wave-cut bluffs on faint inter-valley swells; and should very gradually ascend to greater altitude and greater relief at an interior divide, beyond which similar features would be repeated in reverse order to a farther ocean. The survival of large mountain-like hills along the interior divide where the initial upheaval was greatest is not inconsistent with the occurrence of a well developed peneplain—broad swells of gentle convexity between wide valley floors—over the greater part of the area between the divide and the ocean. Penck has proposed the term, *mosore*, for the residual hills that survive along the divide, not by reason of greater resistance, but by reason of representing a greater original mass to be consumed. From the *mosores* along the main divide, gradually dwindling trains of hills would follow the secondary divides. There is no break in the long sequence of slow changes by which the smaller hills of the secondary divides and the larger hills of the main divides are gradually reduced to so small a relief that they, too, may be regarded as part of a peneplain. The term peneplain should therefore be taken as especially applicable to certain advanced phases of land sculpture not sharply separated from the phases that precede and follow.

If a peneplain have a breadth of 1,000 miles or more, or if a peneplain be developed in the interior of a large continent, its interior part—not merely the residual hills of fairly strong relief, but also the gently undulating swells that rise but little over the broad valley floors—may have altitudes of from 1,000 to 3,000 feet or more above sealevel. Hence an evenly uplifted peneplain, now undergoing dissection, should not be expected to stand everywhere at the same altitude, and the present altitude of even its best developed parts should not be taken as necessarily giving a measure of its uplift, as if it had previously stood at sealevel. The uplift may have been several thousand feet less than the altitude. Cvijic has emphasized this point in his discussion of the physiography of the Balkan region. Similarly, if the coastal two-thirds of a broad peneplain be flexed or faulted down near or beneath sealevel, while the inner third remain at its former altitude, the rivers there will at once proceed to incise new valleys beneath their former valley floors; hence the mere occurrence of valleys incised in a peneplain should not be taken as evidence of uplift. Philippson has urged the importance of this interesting principle in an account of the Slate Mountains of the middle Rhine.

A peneplain formed in a region of varied structure will be first developed in areas of weak rocks, wherever they are situated; it will be later developed in areas of moderately resistant rocks; and by that time the weak-rock areas may be degraded to true plains. The most resistant rocks will long survive as knobs or ridges, now commonly known as monadnocks.

SUBSEQUENT STREAMS AND VALLEYS

The development of subsequent streams along belts of weak structure and the corresponding diminution of consequent streams is a characteristic feature of a well advanced cycle of erosion; and while subsequent streams are developing along belts of weak structure consequent divides will be largely replaced by subsequent divides on belts of resistant structure. But be it noted that the physiographic value of these two stream terms does not lie so much in the indications that they give of stream and valley origins as in the suggestions that they offer regarding the relation of the streams and valleys to their surroundings. A consequent stream or valley following the original slope of a body of inclined stratified rocks will usually have similar rocks and similar forms on both sides; but subsequent streams and valleys are usually characterized by different rocks and by different forms on the two sides; and, furthermore, in a region of slanting structure, where a master consequent is joined by one subsequent stream, it will usually be joined also by another subsequent stream coming from the opposite direction, both subsequents being developed on the same tranverse weak belt.

It is curious to note that the term subsequent, which has been proposed to name a class of streams and valleys in southern Ireland clearly described by Jukes in 1862, has not gained general acceptance among American geologists and physiographers, not even among those who adopt Powell's trio of 1875—consequent, antecedent, and superimposed (shortened by McGee to superposed). Yet it has been pointed out that, by reason of Powell's failure to extend the trio to a quartet by adding subsequent as a fourth member, he was led into serious errors in the interpretation of the streams of the Uinta Mountains; and that Dutton made similar errors in the region of the Colorado Canyon of Arizona for the same reason. Even Gilbert referred to Powell's trio as if it contained a complete genetic classification of streams. Whether the name "subsequent" should be used for the fourth member of the group is unimportant; but that no fourth member should be recognized is a serious mistake. The spontaneous development of subsequent streams in regions of tilted, strong and weak strata is an essential process in the advance

of the cycle of erosion. The addition of three other classes of streams—insequent, obsequent, and resequent—thus enlarging the original trio to a septet, is a refinement of much less importance than the recognition of the class of subsequents.

THE GEOGRAPHICAL CYCLE AND ITS COMPLICATIONS

Two of my European correspondents have lately written me that they must give up the cycle of erosion because it does not include certain facts to which they call attention. One group of facts is the well-opened valleys in areas of relatively weak rocks; and it is urged that these valleys were never “young” in the sense of being narrow; they were widened as well as deepened while the region was raised. I believe it is true that my own writings do not contain any explicit statement of this rather evident idea; the nearest I have come to it is to say that if a region of resistant rocks be slowly uplifted its valleys will be widened as they are deepened. “In such a case there would have been no early stage of dissection in which the streams were enclosed in narrow valleys with steep and rocky walls; the stage of youth would have been elided and that of maturity would have prevailed from the beginning, but with constantly increasing relief as long as uplift lasted.”² Immediately mature valleys of this kind would evidently be much more common in areas of weak than of resistant rocks;* it may indeed be a rare exception to find “young” valleys, in the sense of narrow, steep-sided valleys, in weak-rock areas. In such cases the valleys are probably, Minerva-like, born mature. It is certainly a puzzling and regrettable omission not to have explicitly stated a matter as manifest as that; but what is still more puzzling is why the omission of a subordinate matter of this kind should be regarded as a reason for discarding the whole scheme of the cycle of erosion. The omission clearly gives reason for amending and improving the scheme; but, in view of the abundance of regions in which typical “young” valleys are found in resistant rocks and in which a relatively rapid uplift is thereby proved, the scheme of the cycle seems to me still worth preserving, as well as worth improving as far as possible.

Even if the general presentation of the scheme sets out from a region of relatively resistant rocks uplifted with comparative rapidity, in which the first-cut valleys of the larger streams are typically “young,” the

² Complications of the geographical cycle. Proc. 8th Internat. Geogr. Congr., 1904. Washington, 1905, pp. 150-163; see p. 153.

* Since writing this article I find that explicit, though brief, mention of the more probable occurrence of immediately mature valleys in weak than in hard rocks is made in my “*Erklärende Beschreibung der Landformen*,” 1912, p. 147.

presentation may soon be advisedly expanded to include regions of resistant rocks which are uplifted slowly and in which the first-cut valleys of the larger streams are maturely open or "mature-born" from the beginning; also regions of weak rocks in which, even if the uplift be relatively rapid, the first-cut valleys will be "mature-born"; and in which, if the uplift be slow, the first-cut valleys may be deepened so little in excess of the down-wearing of the inter-valley uplands that the general expression of the surface will at once be "old." Indeed, one may conceive of a region that, after a first very slow uplift, is uplifted more rapidly, but eventually stands still for an indefinite period; and in such a case the expression of the first-developed valleys would be "old"; then as the rate of uplift increased, the "old" valleys would be first incised by "mature," and then by "young" valleys; and finally the "young" valleys would, during the ensuing still-stand period, gradually gain the appearance of "mature" and "old" valleys. Nevertheless, it does not seem advisable to base the general terminology of the whole scheme on so special a case, but rather to modify a generally applicable terminology so as to adapt it to such a case and to various other cases, as need arises.

The other dissenting correspondent proposes to give up the scheme of the cycle because he has found that the small headwater streams of an uplifted and partly dissected peneplain occupy wide-open but shallow valleys, even though the trunk rivers flow in narrow, deep, and steep-sided valleys. I had myself come upon such headwater valleys during an excursion in central France in the winter of 1898-99, and have published an explicit account of them, as well as what seems to me a simple and sufficient explanation of them, in my Berlin lectures of 1908-09.³ The general scheme must therefore be modified so as to recognize that, even if trunk rivers incise typical "young" valleys in an uplifted peneplain, their little headwater branches will probably have "mature-born" valleys from the beginning of the new cycle of erosion. Hence my feeling is here again: Modify the scheme to include this principle as a matter of course; but why give up all the rest of the scheme because a modification is needed here!

CLIMATIC CHANGES DURING A CYCLE OF EROSION

But besides these two correspondents there are other geographers, particularly Hettner of Heidelberg and Passarge of Hamburg, who reject the scheme of the cycle as essentially incorrect in omitting many

³ Die erklärende Beschreibung der Landformen. Leipzig, 1912. See pp. 62, 259.

details and complications which they hold to be indispensable. Passarge, for example, ascribes so great a value to past changes of climate that he is disinclined, to say the least, to regard any existing mature or old land form as the product of a one-climate erosion cycle; not merely that the climate would change during the progress of a cycle from cold and rainy on the initial highlands of an uplifted region to warmer and drier on the old worn-down lowlands; but that, by reason of the shifting of climatic zones, the tilting of the earth's axis, and other possible causes, the processes of "normal" subaerial erosion in middle latitudes, for example, are not likely to endure through so long a period of time as an erosion cycle. He is therefore unwilling to look upon most existing land forms as the product of the prolonged action of their present-day erosional processes. He questions the sufficiency of soil creep on the forested slopes of subdued mountains, like those of North Carolina, to continue the degradation that such mountains have already suffered, and ascribes their present form to the action of some other-than-normal processes in the past; similarly, he discredits the explanation of the *Inselberglandschaften* of sub-arid east Africa—isolated residual mountains rising sharply over degraded rock-plains, like those of southeastern California—by the processes now in operation upon them, and calls in the aid of one or more pluvial periods, even though the visible forms give no evidence of pluvial action.

That there have been climatic changes during the progress of certain cycles of erosion is plain enough in glaciated regions, and also in certain subarid regions where the records of extinct lakes are still preserved; but if the Great Basin of Utah and Nevada be taken as a sample of such a subarid region, the remarkable thing about it is the relatively trifling amount of work that was done there during the Quaternary humid epochs; they were mere transitory episodes in the immensely longer period or cycle of erosion that would be required for the general degradation of the region to a low peneplain. Where the work of the humid episodes is not recorded in lake-shore terraces or cliffs or in basin-floor sediments, it is not recognizable. The forms of the Great Basin are essentially those of a long-continued subarid cycle of erosion, on which the details produced during the brief episodes of humidity are of very subordinate value. Hence, while the effects of changes of climate should, of course, be considered wherever necessary, it is practically helpful to discuss steady-going cycles of erosion during which a normal (humid), or subarid, or other climate has prevailed, and to apply such discussions to the description of regions like the North Carolina mount-

ains or the Great Basin ranges. As far as my inquiries have gone, American geographers and geologists do not share Passarge's misgivings on this matter.

MISCONCEPTION OF THE GEOGRAPHICAL CYCLE AS A RIGID SCHEME

The various objections to the general scheme of the cycle of erosion above alluded to are, in my own opinion, founded chiefly on a misapprehension of it as a rigid and complete concept. It has never been considered either rigid or complete in my mind, but rather a growing idea, always plastic, so that it might be corrected where wrong, or modified and extended where accommodation is needed for new facts and processes. The scheme was first conceived simply in relation to ordinary or "normal" erosion by rain and rivers, by weather and water acting on a landmass of horizontal structure; it was slowly extended to include the action of the same normal processes on various kinds of structures; and later to include various kinds of processes; yet even in the first statement a certain breadth of view was reached, for it was there said:

"The channels [valleys] will be narrow and steep walled in regions of relatively rapid elevation, but broadly open in regions that have risen slowly; and I believe that rate of elevation is thus of greater importance than climatic conditions in giving the canyon form to a valley."⁴

It is quite possible that a misconception regarding the scheme has arisen from the fact that certain brief presentations which I have made of it have emphasized the elementary case of a region which first suffers a rather rapid uplift and which thereafter stands still for an indefinitely long period,⁵ and have given less attention to cases of greater complication, such as those of slow and of variable uplift alluded to above. But even the brief mentions made of possible complications supplementary to the elementary case appear to me quite sufficient to show that they also inhere in the generalized concept of upheaval at various rates and in various manners, associated with degradation by various processes in various combinations. Such complications and variations would not characterize a rigid scheme into which the facts of nature must be forced to fit, as if it were Procrustes' bed; but they certainly do characterize a plastic scheme, the very essence of which is its capacity to adapt itself to the facts of nature, and the main object of which has

⁴ Geographic classification, illustrated by a study of plains, plateaus, and their derivatives. *Proc. Amer. Assoc.*, 1884.

⁵ The geographical cycle. *Geogr. Journ.*, 1899.

The geographical cycle. *Verhandl. VII Internat. Geogr. Kongr. Berlin*, 1899. 1900, 221-231.

always been to treat the forms of the land in a rational and revolutionary manner.

ESSENTIAL FEATURES OF THE GEOGRAPHICAL CYCLE

The last point deserves fuller statement. The essence and object of the scheme do not lie in its name, "cycle of erosion," to which indeed objection has been made because its processes are not circular in the sense of returning at the end to their beginning—an objection that has less weight today than when it was first offered, because it is now generally recognized that not only must plains and plateaus be in the end worn down to surfaces about as smooth as those with which they began their cycle of change, but also that most of the existing mountain ranges of the world began their present cycle of erosional change in peneplains very much like those down to which they will be again eventually worn if no disturbance happens. Nor do the essence and object of the scheme lie in the adoption of such words as young, mature, and old—two of them, young and old, having been introduced by Chamberlin—as names for the successive stages of an ordinary cycle of erosion; any other names that the geographical world prefers will serve; but it is a satisfaction, *quand même*, to know that a physiographer so philosophical as Gilbert held that the analogy on which this terminology is based is good because it indicates a "close resemblance in some striking particulars, coupled with differences in other respects;" and it is truly gratifying to read his opinion:

"In my judgment, there are few groups of terms which serve better than does this group the purpose of concisely expressing an idea. Its strength inheres, first, in the aptness and completeness of the analogy, and, second, in the perfect familiarity of the group of facts to which the unfamiliar facts are likened. . . . The aptness and the familiarity make the terms permanently mnemonic, so that the use of any one of them brings to mind not only the sequence, but relative position in the sequence."⁶

The essence and object of the scheme of the cycle does not lie in its terminology, but in its capacity to set forth the reasonableness of land forms and to replace the arbitrary, empirical methods of description formerly in universal use, by a rational, explanatory method in accord with the evolutionary philosophy of the modern era. All the older descriptions of land forms treated each form by and for itself. The idea that certain groups of forms may be arranged in a genetic sequence based upon structure, process and stage, and the further idea that the

⁶ Style in scientific composition. *Science*, vol. xxi, 1905, pp. 28-29.

different form-elements of a given structural mass are at each stage of its physiographic evolution systematically related to one another, were not then recognized. The terminology by which these ideas are set forth is a subordinate matter, although it is of course desirable that some one reasonably consistent terminology should be generally adopted as a matter of convenience. But it is today inevitable that the fundamental ideas of the reasonableness of land forms and the systematic relations of their elements should be accepted and made use of in their description.

The reasonableness is not exhibited only in the sequence of forms and the systematic relations of their elements during the uninterrupted progress of a single cycle; it is also exhibited, although in a more complex manner, when one cycle is interrupted at any stage of its progress by a movement which introduces another cycle; or by a volcanic or climatic accident which for a time disturbs its ordinary progress. Great practical advantage follows from the recognition and utilization of these ideas, for they serve to impress, first, the helpful physiographic principle that every structural mass has, at any stage of its erosional development, a reasonable surface form; and, second, the equally helpful principle that if a structural mass is moved at any time, the form that it had gained when the movement took place must always be specified, as well as the new attitude into which it was placed by the movement and the changes it has suffered since the movement—always provided that the changes since the movement have not wholly obliterated the pre-movement forms; in that case, whatever importance the movement may have in a geological study, geographical study is not responsible for it.

INDUCTION AND DEDUCTION IN THE SCHEME OF THE CYCLE

A frequent misconception of the scheme of the cycle is one that regards it as based chiefly on deduction. It is true that various expositions of the scheme have been cast in a deductive form, because that is the most convenient form in which to present a general idea to mature readers; and it is also true that, as in all geological and physiographic reasoning, deduction frequently either anticipates observation or fills in gaps where observation is lacking; but to imagine that the scheme as a whole is deductive, in the sense of being contrived independent of observation and induction, is absurd. Its different phases are all composite results of seeing and thinking, and of thinking and seeing; and it would be impossible today to state in just what proportion these two complementary processes have contributed to the total results. As a matter of fact, even the penultimate stage of a normal cycle of erosion first

came to my attention and understanding through observation in the summer of 1883, when I was studying the series of rocks below the Cretaceous coal horizon in Montana for the Northern Transcontinental Survey, under the direction of Professor Pumpelly. Areas of the Great Plains of nearly horizontal strata that I then traversed gradually came to be understood as plains of degradation, because they were here and there surmounted by lava-capped tables and dike-ridges, or even by mountainous residuals held up by the extra resistance of a network of dikes. It was several years after that beginning was made before the idea of peneplanation was extended to regions of disordered rocks in Pennsylvania and New England; and then again the facts observed, compared, and generalized in inductions preceded the attainment of the explanation by deduction.

The same is true regarding the scheme of the cycles of marine abrasion and of glacial erosion. As to the latter, it was the sight of the hanging side valleys high above the broad floor of the valley of the Ticino, the Val Leventina, in the southern Alps, which first led me to search for their explanation by a strong deepening of the main valley by glacial erosion in 1899, a year after Gannett had, then unknown to me, seen similar facts about Lake Chelan and reached a similar explanation for them. But the disappointing thing about this advance is that it had not been made deductively years before; and the fact that it was not so made must be explained chiefly by the inattention of geologists and geographers to the immense aid that deduction gives to observation when the origin and the meaning of things are searched for.

DEDUCTION IN THE SCHEME OF THE ARID CYCLE

An exception to the statement that induction and deduction have usually gone hand in hand, in so far as my own work on cycles of erosion is concerned, must be made in the case of the arid cycle; for there, following a clue suggested by Passarge's account of his observations in South Africa, I deduced a whole sequence of changes far in advance of their observational verification; and in spite of repeated search in the records of explorers of desert regions, many of the deduced stages are still without their observed counterparts. If the records of these explorers gave specific examples of observed forms that contradicted the features of the deduced forms, the scheme of the arid cycle might be condemned as wrong; but as a matter of fact their descriptions are, as a rule, so vague that it is impossible to know just what sort of forms they are describing. Their records neither prove nor disprove the arid cycle.

A few examples of high-level intermont basins are known in Tibet, the wet-weather drainage of which appears, from the fragmentary descriptions now available, to have been rather recently diverted to adjoining basins of lower level; but the accounts of the connecting gorges are so brief, so inadequate, that it is impossible to say whether they are consequences of spontaneous captures or not. In my own experience, the nearest approach to the capture of a higher arid basin by a lower one was seen in 1914 from a train on the Western Pacific Railroad about 100 miles west of Salt Lake City, where ascent was made through a mountain notch from a lower to a higher basin floor; but much extension of the gorge by headward erosion will be necessary before the whole drainage of the higher basin will become tributary to the lower one.

UNLIKE USE OF THE CYCLE IN GEOLOGY AND GEOGRAPHY

A closing paragraph may be given to the unlike use of the cycle of erosion by geologists and geographers. For geologists, cycles of erosion, either very brief or nearly complete, are events in the past history of the earth, and as such are to be treated like any other past events. Their recognition has contributed greatly to the completion of those chapters of geological investigation which are concerned with the evolution of land areas, by showing not only that erosion has taken place at one epoch or another, but also by making it clear how far erosion proceeded in each epoch. The problem of the Great Basin ranges might be here reviewed to advantage, for it was not correctly solved until the cycles of erosion that it involved were explicitly recognized and defined. On the other hand, for geographers—or rather for those geographers who are particularly interested in the careful and intelligible description of the stage-setting in which the human drama is played—the scheme of the cycle of erosion has its chief value not as a means of reproducing the past, but as a means of describing the present.

In illustration of this point: If the district of Snowdon, in north Wales, or of James Peak, in the Rocky Mountains front range, is described by a geologist, each of the successive incomplete cycles of erosion, normal and glacial, that the mountain and its district have suffered deserves equal attention and all of them should be set forth in historical sequence. If Snowdon or James Peak is described by a geographer, its existing form should be directly stated as a consequence of the successive cycles of erosion it has suffered. The sole reason for such explanatory description by a geographer is, not that it gives a knowledge of the past, but that it gives a more effective knowledge of the

present than any empirical description does. Both the mountains here named exhibit the subdued forms of late-mature normal erosion; that is, dome-like summits from which rounded spurs descend in various directions; and in both these normal features are greatly modified by the recent excavation of huge glacial cirques in the valley heads between the diverging spurs; hence the present remnant of the dome-like summit is undercut on several sides by great cirque-head cliffs, and not far below the summit remnant the deepening and widening of the glacial troughs reduces the sloping spurs to sharply serrate, coxcomb-like crests. The single word "recent," used to qualify the excavation of the cirques and troughs, suffices to show that postglacial changes are small. The distinction here made between the use of the cycle scheme for geological and geographical purposes deserves more attention than it usually receives.

VARIATIONS OR SPECIFIC DISTINCTIONS: WHICH? ¹

BY RICHARD SWANN LULL

(*Read before the Paleontological Society December 30, 1921*)

CONTENTS

	Page
Introduction.....	599
Age distinctions.....	600
Sex distinctions.....	600
Ontogenetic variations.....	601

INTRODUCTION

In the search for criteria for specific diagnosis, especially in fossil mammals, too little heed seems to be given by the average systematist to a number of aspects of individual variation which are manifestly such in living forms. As a consequence, our paleontologic literature is burdened with a vexatious synonymy which requires extensive monographic study to unravel. Too often the description is based on excessively fragmentary material, whereas for enduring work not only should the type be as adequately represented in all of its essential parts as possible, but as large a series of individuals as may be had should be used with the idea of detecting such characters as are merely individual and such as are truly diagnostic of the species.

Among recent forms, three directions of variation are easily recognized—those due to age, to sex, and to environment—under the last of which comes the direct influence of climate, mainly the degree of moisture, to a less extent of temperature, of altitude, and of peculiarity in life conditions and consequent habits, with physical as well as physiological reaction. Of course, the environmental variations may give rise to what are called geographical variants, which are established in the heredity, and as such may be incipient species, or the modifications may be individual or ontogenetic only, to disappear as soon as the conditions which gave rise to them change.

¹ Manuscript received by the Secretary of the Society March 28, 1922.

AGE DISTINCTIONS

There is little difficulty, as a rule, in detecting relative age, especially in mammals in which the teeth are preserved, but in certain instances, notably among the camels and horses, tooth proportions change so much that comparative measurements should be studied with great caution. The development of crests on the skull, as in the adult male gorilla, is conceivable as a response to increasing muscular power with maturity, as well as alteration of jaw form, especially toward the muzzle, as old age approaches. Badly worn teeth, especially in a carnivore, would certainly imply a necessary dietary change, with a consequent muscular modification, probably degeneration.

To what extent age characters would modify the bodily skeleton, to the confusion of the systematist, is not clear.

SEX DISTINCTIONS

In the modern mammal, these are seen not alone in pelage, which is, of course, lost to the paleontologist, but in actual bodily changes aside from differentiation of size—such, for instance, as the mighty shoulders of a bull bison, which react not alone in muscle, but in bone as well. It may readily be inferred that such must also have occurred among titanotheres and other huge well armed beasts.

Antlers and horns in the extinct deer and antelope are, of course, readily recognized sex distinctions, as are doubtless the presence or degree of development of tusklike canines and incisors; but rarely, I think, does one realize the extent of the mechanical reaction of the remainder of the skull to the presence or absence of such structures. This was brought before us in a very vivid and disquieting manner recently in the case of two skulls of the Chinese water deer, *Hydropotes inermis*, in the Peabody Museum Osteological Collection—one a male, the other a female. The former possesses great laniary canine tusks, whereas in the latter the canines are very small, inwardly curved, and probably hardly penetrated the gum. The animals were both fully adult, but the teeth of the male show a somewhat greater degree of wear.

The other skull distinctions follow: Length, male, 172 millimeters; female, 154 millimeters: bizygomatic diameter, male, 74 millimeters; female, 64.5 millimeters.

The cheek teeth of the male are larger, especially the premolars, of which P^2 is more complex, the mesostyle being more pronounced. The molars are very narrow in the female and there is no trace of the internal

basal pillars which are present in the male. The premaxillaries differ markedly in shape, those of the male being more closely united and converging to a point. The premaxillary-nasal suture in the male is little more than half the length of that of the female.

A very marked distinction lies in the lacrymal, which is larger and of different outline in the female and has a flush surface, whereas that of the male bears a deep facial depression. The position of the lacrymal duct also varies, as it is single and entirely within the orbit in the female, double and partly external in the male. The facial vacuity formed between the lacrymal, maxillary, and frontal in the female is very much larger and is bounded also in part by the nasal in the male. The frontal foramina are much larger, lie nearer the orbital rim, and their grooves are much more pronounced in the male.

The position of the infra-orbital foramina is farther forward in the male and the foramina are more complex. The maxillary bone is more deeply molded between the teeth in the male, which, together with the deep lacrymal fossa, is correlated with the greater development of labial muscles to draw the lips back from the tusks.

The cranium of the male is smoother and the less pronounced temporal ridges fail to meet to form a sagittal crest such as is present in the female. The shape of the occipital region and of the condyles and paroccipital processes also differs. The form of the palate varies, together with its posterior limitation and the outline of the palato-maxillary suture, and there are differences in the position and shape of the basicranial foramina.

These are characters which are severally used repeatedly by our mammalian systematists in specific differentiation, and I venture to believe that were these skulls fossil and their relationship unknown, they would be considered as specifically if not subgenerically distinct.

ONTOGENETIC VARIATIONS

Humidity reacts most strongly upon coloration of the coat, whether of hair or feathers. It is not clear that it would affect the form or structure, especially of the bones and teeth in an individual, although, of course, there is a racial or evolutionary response to humidity and aridity, both directly and indirectly, through adaptation to a changed vegetative environment.

Local or geographical color phases or varieties of mammals and birds may be simulated in the individual under artificial conditions and may be, therefore, merely ontogenetic repetition rather than truly racial. Thus, five lions belonging to the grayish buff *Felis leo massaica*, which

were captured near Nairobi, British East Africa, and confined in the Washington Zoo for five or more years, changed in color so much, increasing with each successive molt, that they finally resembled that of the race *F. leo nyanzæ* of the more humid Victoria Nyanza region.² Beebe³ experimented on birds, increasing the pigmentation with successive molts by confining them in a superhumid atmosphere. The inference is that with both birds and lions the color change was due to the direct effect of humidity, as that of Washington is notably greater than of the Nairobi region of Africa. The park-reared animals also had much longer, finer manes and elbow tufts than did wild-killed lions of the same race.

Another effect of environment on the Washington lions is, however, more pertinent to our thesis, for in this case it took the form of a muscular and bone response to a change of living habits, due to the fact that the park-reared animals were fed on man-killed food and were not required either to kill or carry off their prey. Thus Hollister says (page 190):

"The skulls of lions and other large carnivores which habitually kill quantities of heavy game are greatly influenced in a definite way by the development of the principal muscles used in gripping, holding, tearing, biting, and shaking. If the animals are captured when young and reared in confinement, these particular muscles are little developed and the bone at the region of origin or insertion is little changed by their influence. The bones then retain certain characteristics of juvenility and develop along wholly different but uniform lines from that of the wild-reared animal.

"Changes in the skull which would be accepted as of 'specific' or possibly of 'generic' value in wild animals from different regions are thus produced in the life of a single individual within from five to seven or eight years, almost as rapidly as if by 'mutation.' . . . Might some such change not happen in a state of nature? . . . If all the ungulate mammals of Africa, or in some one extensive region, were swept away in a few years by a plague like the rinderpest, would the lion die out, or would he completely change his habits in one generation and become a feeder on mice, squirrels, birds, and fruit? In the latter case, would not the enforced disuse of the powerful mechanism for the destruction of zebras, hartebeest, and larger game produce in one generation, as with the park lions, a type of skull wholly different from that now known in a state of nature?"

The specific changes seen in the park lions were greater relative and actual zygomatic breadth, large rostra, great distance across the base of the skull at the mastoids. While actually measuring less in condylobasal (greatest) length than many of the wild *massaica* skulls of equal age,

² N. Hollister: Proc. U. S. Nat. Mus., vol. 53, 1917, pp. 177-193.

³ C. W. Beebe: Zoologia, vol. i, no. 1, 1907.

they have a far greater zygomatic breadth than any, averaging about 30 millimeters more in the males and 20 millimeters more in the females. Again, while the external cranial measurements of the wild lions are less than in park animals of equal age, the cranial capacity averages 50 cubic centimeters more for the males and 40 cubic centimeters for the females, as the cranial walls are actually thicker in the park-reared specimens. Thus it will be seen that the ratios between skull measurements, which have been used as specific criteria by paleontologists, may change materially during the life of a single individual as a direct result of forced change of habit which may endure for but a generation.

On studying species lists of African⁴ and North American⁵ mammals, the following features are apparent: The number of described species and subspecies of a genus seems to bear an inverse ratio to the size or, more properly, to the migratory powers of the animal. Thus, in North America, of the larger indigenous mammals there are:

Bison, 2 varieties.

Rangifer, 12 species, 2 subspecies.

Ursus, 20 species, 12 subspecies.

And of the smaller forms:

Vulpes, 15 species, 9 subspecies.

Canis, 24 species, 2 subspecies.

Mustela, 28 species, 30 subspecies.

Sorex, 23 species, 40 subspecies.

Lepus, 15 species, 37 subspecies.

Sciurus, 36 species, 79 subspecies.

Microtus, 43 species, 38 subspecies.

Peromyscus, 43 species, 113 subspecies.

As these are largely geographic variants, it would seem as though the smaller forms have a much more limited sexual environment than have the larger; so that small variations, evidently largely climatic, are more apt to continue as distinctive characters, although probably frequently ontogenetically repeated, but under hereditary control. Enforced migration or climatic change might well produce such alteration of color as to show that many so-called subspecies—such, for instance, as those of *Peromyscus*—are merely instances of local polymorphism.

Detailed studies of the lists of East African forms contained in the United States National Museum only serve to emphasize the same conclusion. Some of the so-called varieties, as of hunting dogs (*Lycaon*),

⁴ N. Hollister: U. S. Nat. Mus., Bull. 99, pts. 1 and 2, 1918-1919.

⁵ G. S. Miller, Jr.: Ibid., Bull. 79, 1912.

however, have been based on seasonal condition of the pelage, which causes marked color change.

But the paleontologists are not concerned with fur and feathers, and I am now inclined to believe that they are not such great offenders in the multiplication of non-existing species as are their recent zoological colleagues, especially when one realizes the fact that any fauna, as the vertebratist knows it paleontologically, may cover hundreds of generations as compared with tens or even fewer of living creatures. There is need, however, of more consideration of these several aspects of variability and a keener visualizing of habitat limitations and life conditions, if our descriptive work is to have a lasting value.

VOLCANIC ASH BED IN THE ORDOVICIAN OF TENNESSEE,
KENTUCKY, AND ALABAMA¹

BY WILBUR A. NELSON

(Read before the Society December 29, 1921)

CONTENTS

	Page
Introduction.....	605
Extent of ash deposit.....	606
Description of bentonite outcrops.....	606
Conditions existing at the time of ash deposition.....	608
Thickness of bentonite layer.....	609
Location of ancient volcano.....	610
Amount of ash ejected.....	610
Ash falls from historic volcanoes.....	611
Ash falls from prehistoric volcanoes.....	611
Extent of ash falls during Lowville time.....	611
Settling of volcanic ash in salt and fresh water.....	612
Evidence of igneous activity in eastern Kentucky.....	613
Report of E. S. Larsen on Tennessee bentonite.....	613
Analyses of bentonite and leverrierite.....	614
A new theory of the formation of bauxite deposits.....	615

INTRODUCTION

The determination of a greenish, sticky, clay forming bed about two feet thick, observed in Bedford County, Tennessee, in 1920, as bentonite, an altered volcanic ash,² started a search for additional outcrops of this deposit and the collection of data that would bear on its origin, extent, and method of deposition. This paper is primarily a progress report on this subject, on which it is hoped much additional work will be done. The first observation of this clay deposit was made at the settlement of Singleton, in Bedford County, Tennessee, at which place it measured 21 inches thick.

¹ Manuscript received by the Secretary of the Society February 23, 1922.

² E. S. Larsen: Personal letter, 1921.

EXTENT OF ASH DEPOSIT

The southernmost occurrence of the ash deposit thus far known is at Bessemer, Alabama, a suburb of Birmingham, 145 miles south of Singleton, Tennessee. At this place it is reported to measure from 14 to 18 inches thick. The northernmost exposure seen to date is at High Bridge, Kentucky, 190 miles to the north of Singleton, Tennessee, where it measures from 4 to 10 feet thick. This makes the known north and south extension of this ash fall 335 miles.³ This ash bed may well have extended much farther to the south and north than the limits mentioned, and thinned out gradually as the distance became greater and greater from the volcanic center. Several inches of impure clay have been found 50 miles northwest of Singleton, around Nashville and Franklin, where this ash horizon dips under the surface, on the western side of the Nashville dome. The limits of the bentonite bed undoubtedly extend still farther westward than Franklin. To the east beyond Dayton, Tennessee, the bentonite is undoubtedly now absent, as this area was occupied by a landmass and the ash bed would have subsequently been removed by erosion. To the north of High Bridge, the point where the thickest bentonite was seen, no work has been done, yet undoubtedly the northern limits of the bentonite must be north of the Ohio River, in middle Ohio and Indiana. The limits of the area covered by this bentonite bed may have been from just south of Lake Erie on the north to the Gulf of Mexico on the south, and from western Virginia and North Carolina on the east to Missouri and Arkansas on the west. Such an elliptical area is about 800 miles long by 450 miles wide. Before attempting any estimate of the amount of ash deposited over this area, it is necessary to determine as nearly as possible the conditions under which the ash was deposited and the location of the volcano producing it.

DESCRIPTION OF BENTONITE OUTCROPS

The bentonite occurs at Singleton, Tennessee, 8 feet below the top of the Lowville limestone of the Black River group, which is overlain by the Hermitage formation of the Trenton group. To the northeast, at Pikeville, Tennessee, the same section occurs. At Dayton, Tennessee, 15 miles to the east of Pikeville, the section is the same, with the exception that the limestones lying on top of the bentonite have become somewhat shaly

³ Since this paper was given at Amherst, Dr. Walter A. Bucher, of the University of Cincinnati, has reported to the author the occurrence of this bentonite bed in well number 2, Sinking Spring Oil Company, in the southwest corner of Perry County, Ohio, at a depth of 1,242 feet. This is 110 miles north of the High Bridge, Kentucky, outcrop.

and have a light red, purplish color in a number of layers. Six miles to the east of Dayton the bentonite was not found, but the limestone lying on top of the Lowville rocks is a very dark red limy shale, containing fossil sun cracks, being either a near-shore phase of the Hermitage formation or the Le Ray part of the Lowville. At High Bridge, Kentucky, the section has been described by Ulrich,⁴ who has the following to say about the bentonite layer:

"Near the middle of the beds there is a very soft clay layer, about two feet in thickness, nearly white, with often a greenish tinge. Some fragments were seen in which the green color is decided. It has a peculiar unctuous feel, is readily cut with a knife, and when exposed a short time to the atmosphere breaks up into small flakes."

At this place the bentonite (which is about 5 feet thick) rests on Lowville rocks, locally known as Tyrone limestone, while just above the bentonite is 18 feet of thin-bedded, dove limestone with some shaly layers, being upper Lowville, known locally as Le Ray limestone. On top of the Le Ray is 26 inches of the Curdsville formation, which here occurs between the Lowville and the Hermitage. At the base of the Curdsville there occurs an impure layer of the clay, representing reworked volcanic ash. As the locality at Bessemer, Alabama, is in the Woodward Iron Company's mine shaft, the sides of which are now cemented, it is impracticable to get any section, but it is stated by the geologist of the Tennessee Coal, Iron and Railroad Company⁵ that the "green clayey material" (the bentonite as now known) occurred about 75 feet below the big seam of red ore, and apparently just on top of the Chickamauga limestone. As the bentonite was known to occur in the Birmingham district, a day was spent on Red Mountain, just east of the Woodward Iron Company's shaft, and the bentonite was found to outcrop at two places. The first exposure was seen in the edge of Birmingham, on the Twentieth Street cut, on the west side of Red Mountain, about 100 yards from the crest of the road. The second exposure was seen on the Altamont-Mount Terrace road, near the crest of Red Mountain, which at this point is built up as a suburb of Birmingham. The bentonite occurs 32½ feet below the Silurian-Ordovician contact and rests on a ripple-marked chert layer at the top of the Lowville formation. It is overlain by between 3 and 4 feet of grayish blue, thick-bedded limestone containing a number of thin chert layers. Limestone beds which vary in lithology extend from the bentonite bed to the Silurian contact.

⁴ E. O. Ulrich: Correlation of the Lower Silurian horizons of Tennessee and the Ohio and Mississippi valleys with those of New York and Canada. *American Geologist*, vol. 1, 1888, p. 107.

⁵ Letter of A. S. Blair, Geologist of the Tennessee Coal, Iron and Railroad Company.

CONDITIONS EXISTING AT THE TIME OF ASH DEPOSITION

This ash-fall thus occurred just before the close of Lowville time, which was a period of much oscillation of the earth's crust and intensive warping. The ash does not mark an unconformity, but does slightly precede the unconformity which exists in the Southern States between the Black River and Trenton groups. It is interesting to note that after the ash deposition the Le Ray limestone deposited to a greater thickness as one goes north, there being eight feet of Lowville belonging to the Le Ray time at Singleton, Tennessee, while 190 miles to the north, at High Bridge, Kentucky, there is 18 feet of this same limestone. At High Bridge, Kentucky, the Le Ray formation of the Lowville time is overlain by about two feet of reworked ash, showing that the earth to the east or southeast was probably elevated so that the ash was either carried away by shore currents or washed off of the landmass to the southeast or east and redeposited at the base of the shore phase of the Curdsville Sea, an arm of which covered all of middle Kentucky and a narrow strip along the northern part of Middle Tennessee. The conditions existing in the Lowville Sea at the time of deposition of the ash are partly inferred from things seen in the different sections examined. At Pikeville, Tennessee, the bentonite rests on a two-inch chert layer, on the surface of which are well preserved fossil ripple-marks. The parallel lines of these marks extend south 48 degrees east, which would show that if these marks were made by a coastwise current that its direction was north 42 degrees east, or south 42 degrees west, which would be roughly parallel with the shore of the Lowville Sea. This ripple-marked chert has a thin surface coating of brown iron oxide, and also this surface contains large bryozoan fragments, as well as a scattering of flat brachiopods. This ripple-marked chert occurs at High Bridge, Kentucky, and at Birmingham, Alabama, and at both places the bentonite rests on it directly. The presence of such easily recognized ripple-marks at three points many miles apart shows that, in this area at least, a uniform depth of water existed, and the other facts noted would indicate that the sea was comparatively shallow—say, not over 25 feet deep—at the time the volcanic ash fall occurred. It is, of course, possible that the ripple-marks noted were caused by tidal action or by currents which were not coastwise, but were only local shore currents which abutted against the ancient shore obliquely. The fact that the ash was deposited in water is indicated by the bedding it exhibited in the road-cut at Singleton, Tennessee. At this locality the bed is divided into three distinct layers. At the top of the bentonite is a half-inch streak of white calcium carbonate, then 10 inches

of green bentonite with streaks of white calcium carbonate extending through it in nearly vertical lines; then 5 inches of yellowish, sandy bentonite containing rounded grains of quartz, biotite mica, and feldspar, and a basal layer of 5 inches of green bentonite resting on a smooth surface of dark blue, crystalline limestone. This middle coarse layer might have been caused by a shifting of prevailing winds or an increase in their intensity. The contacts between the three layers of the bentonite bed are very regular, but that between the top of the bentonite and the overlying limestone is irregular and, in places, this dove-colored, thinly bedded limestone lies within one or two inches of the top of the second layer of the bentonite bed. This regular bedding with a middle coarse layer of impure bentonite indicates water deposition, practically continuous, but the irregular contact of the bentonite with the overlying limestone shows that the bentonite, after deposition, was subject to erosion, probably by current or tidal action, or by wave action due to a nearer progressing of the shoreline of the Lowville Sea to this point during Le Ray time, when the Lowville Sea probably became greatly constricted, due to the slight warping of the earth's crust.

THICKNESS OF BENTONITE LAYER

When a volcanic ash deposit covers a shallow inland sea like the Lowville was during Le Ray time, the bulk of the ash would finally settle on the sea bottom directly below that part of the sea surface on which it fell. In places local currents might carry and redeposit a small amount of the ash in irregular fashion, but, taken all in all, the greater the distance from the ancient volcano producing this ash, the less would be the thickness of the ash deposited on the sea-floor. This being the case, the present bentonite deposit would get thinner and thinner as one progressed away from the old volcanic center.

The maximum thickness of the bentonite bed measured was at High Bridge, Kentucky, where it is considered to average 5 feet, although as much as 10 feet is stated to occur at one point. To the south of this place, on the Kentucky-Tennessee line, in wells drilled for oil in Pickett County, Tennessee, 4 feet of this bentonite was encountered, while about 5 miles still farther southward, at Pikeville, Tennessee, only 3 feet of bentonite occurs. Southwest of Pikeville, at Singleton, Tennessee, at a still greater distance from High Bridge, Kentucky, the bentonite measured 2 feet thick, and at Birmingham, Alabama, the southernmost place measured, it is only 14 to 19 inches thick. These figures show a gradual thinning of this ash bed as one goes south from High Bridge, Kentucky,

and from these facts it is considered that the volcano producing this ash deposit must have been located either to the east of High Bridge, Kentucky, or a short distance to the northeast. The fact that no ash deposits or bentonite have been recognized in the Lowville formation, where it has been studied in Maryland and Pennsylvania, would indicate that this ancient volcano could not have been located northeast of the Kentucky-West Virginia State line, for if such were the case thick ash deposits, which could not have escaped observation, would have been found in the Lowville rocks of West Virginia, Maryland, and Pennsylvania, even though the prevailing winds at the time of the ash deposition were to the southwest, as the present facts indicate. A study of the paleogeographic maps of the Lowville and succeeding seas shows that a volcano located in eastern Kentucky in the late Lowville time would have been an island volcano.

LOCATION OF ANCIENT VOLCANO

It is therefore suggested that during Lowville time a great volcano existed on an island (somewhere in the area between and including Fayette County, Kentucky, on the west and to Elliott County, Kentucky, on the east) lying 50 to 75 miles west of the long peninsula separating this sea from the ancient Atlantic Ocean. We might visualize many low-lying islands along the edge of the peninsula and extending out into the shallow Lowville Sea, while far out to the west towered this volcanic peak. In the warping of the earth's crust, so prevalent throughout the central and eastern part of America at the close of Lowville time, this ancient volcano exploded in one of the greatest eruptions which, so far as records are decipherable, we know the earth has undergone.

AMOUNT OF ASH EJECTED

A volcano in this general locality, from the facts obtained to date, erupted sufficient ash to form an irregular cone with an elliptical base, having a long axis of possibly 850 miles and a maximum height of 5 feet. Such a cone would contain about 100 cubic miles of material. But a volcanic ash deposit would not be in the form of a flat cone, but would form a cone with a decidedly concave slope; so that it is arbitrarily estimated that such an ash cone as it is thought was formed by this volcano would contain only two-thirds the volume of the true cone, or 66 cubic miles of ash. No account is taken of the considerable amount of volcanic dust that must have fallen as a thin film much beyond the above limits; also,

no account is taken of the great thickness of ash that must have fallen within 15 or 20 miles of the volcano.

ASH FALLS FROM HISTORIC VOLCANOES

The intensity and violence of this eruption can be realized when the amount of ash erupted is compared to eruptions in historic time. Statistics on volcanoes⁶ show that the most violent volcanic eruption on record was that of Tomboro, on the Island of Sumbawa, east of Java, in 1815, which, it is estimated by different investigators, ejected from 26.6 to 50 cubic miles of material. Krakatoa, in 1883, and Katmai, in June, 1912, each ejected about five cubic miles of material. During and after the Katmai eruption its ash-fall was noted as far as 1,200 to 1,500 miles distant.

ASH-FALLS FROM PREHISTORIC VOLCANOES

The occurrence in the southwest corner of South Dakota of clay beds derived from volcanic dust is described by Wherry⁷ as being widespread throughout this section. During late Cretaceous and Tertiary times there was intense volcanic action in the Rocky Mountain region, and these clay beds formed of altered ash deposits are added evidence showing the intensity of such volcanic activity at that time.

A volcanic eruption comparable to any of historic time is described by Capps⁸ as occurring in the upper Yukon. It is estimated that this ancient volcano ejected about 10 cubic miles of material, all of which was deposited on land.

EXTENT OF ASH-FALL DURING LOWVILLE TIME

In an ejection of about 5 cubic miles of material, like Katmai, the ash-fall was noted 1,500 miles away; so it is logical to conclude that in an eruption in which ten times this amount of material was ejected, the ash-fall would be noted at much farther distances from the volcano, and one should expect that the entire Lowville Sea would show traces of volcanic ash in its sediments, as its furthest point from this volcanic center was about 900 miles distant, in the northwest corner of Wisconsin. It is use-

⁶ G. C. Martin: The recent eruption of Katmai Volcano, in Alaska. *Nat. Geog. Mag.*, vol. 24, no. 2, 1913.

⁷ Edgar T. Wherry: Clay derived from volcanic dust in the Pierre in South Dakota. *Jour. Wash. Acad. Science*, vol. 7, no. 19, 1917, pp. 576-583.

⁸ Stephen R. Capps: An ancient volcanic eruption in the Upper Yukon Basin. *U. S. Geol. Survey*, 1915, p. 95.

less to expect to find any evidence of this ash deposit in those areas that were landmasses at that time, as the many periods of erosion that have taken place since then must have undoubtedly obliterated all such ash deposits.

This ash deposit, from the fact that at least a few inches of it may have been deposited in all parts of the Lowville Sea, should be carefully looked for, and can be used as a positive base line for correlation work in the entire area where Black River rocks outcrop in the eastern United States. It should also be looked for carefully in all well cuttings from wells that go through Trenton rocks in search for oil, as bentonite fragments are readily recovered from cuttings of cable tools, and their presence shows that the well is through the Trenton and is in the underlying Black River rocks.

As it is only from those ash deposits which fell in the Lowville Sea that we can look to find a record of the activity of this very ancient volcano, certain suggestions concerning the waters of this sea are hazarded.

SETTLING OF VOLCANIC ASH IN SALT AND FRESH WATER

As a large percentage of the bentonite is very finely crystalline or colloidal and goes into suspension, an experiment was made to determine the effect of a weak solution of sodium chloride on this suspended matter. A small quantity of bentonite from High Bridge, Kentucky, was mixed with distilled water and allowed to stand five days; the amount of bentonite in suspension was decanted and sample number 1 boiled for a few minutes, and after 24 hours all the bentonite was still in suspension. Sample number 2 was boiled for a few minutes with a weak solution of sodium chloride, and after three hours the solution had settled clear. Sample number 3 was added to a cold weak solution of sodium chloride, and the bentonite settled out and left the solution clear in three hours' time. The effect of sea or brackish water on finely crystalline volcanic ash dust can be inferred and account for a comparatively quick settling on the sea-bottom of volcanic ash dust, where the sea water is salt or brackish; but it appears that volcanic ash dust falling on a sea or lake of fresh water would stay in suspension indefinitely, and only the coarser ash particles would settle on the sea-bottom. Such must have been the case in certain Tertiary ash deposits occurring in the Green River beds of Wyoming, Utah, and Montana, in which numerous fossil fishes have been found, and might also account particularly for the altering of certain beds of volcanic ash to bentonite, such as have been described from

different western localities by Hewett,⁹ the bentonite being formed only from the very fine volcanic dust particles where they fall on salt or brackish water and are coagulated and settled on the sea-bottom.

EVIDENCE OF IGNEOUS ACTIVITY IN EAST KENTUCKY

Having arrived at an estimate of the volume of ash material ejected by this volcano, it is seen that this must have been one of the large, deep-seated volcanoes of the earth, and to have been in a region where other evidences of volcanic action and of mineralization, such as accompany such action, occurs. Such a volcano may have, from time to time during the succeeding ages, broken forth for short intervals of time either by ejecting other ash material or by sending out dikes of igneous rocks, theoretically such dikes becoming more basic as time passed on and this volcano reached its old age. Basic igneous rock in the form of peridotite dikes do occur in northeastern Kentucky, in Elliott County.¹⁰ Such dikes, which cut up through the Carboniferous rocks, may represent the last extrusions from the neck of this volcano emanating out of this deep-seated igneous mass many ages after the acid ash fall. It is considered by Phalen that these dikes are of early Mesozoic age.

The presence of these peridotite dikes in northeast Kentucky might be considered as another link in the chain of evidence locating this ancient volcano in this section of Kentucky, and with this added evidence it is felt that this volcano must be buried under the Cumberland Mountains of Elliott or adjoining counties to the south. Additional evidence of volcanic activity in the mountain section 125 miles to the south of Elliott County is shown in the presence of a dike of basic igneous material occurring in Union County, Tennessee, on the east side of the Cumberland Mountains. This dike, which was found by Watkins¹¹ about 1912, is about 30 feet wide and is composed at the present time for the most part of chlorite and serpentine with some garnet and magnetite. This is probably another altered peridotite dike.

REPORT OF E. S. LARSEN ON TENNESSEE BENTONITE

Samples of bentonite from Singleton, Tennessee, were submitted to Esper S. Larsen, of the U. S. Geological Survey, for determination. Larsen states that this material is a decomposed rhyolitic ash that has

⁹ D. F. Hewett: The origin of bentonite and the geological range of related material in Big Horn Basin, Wyoming. Washington Academy of Science Journal, vol. 7, April 4, 1917, pp. 196-198.

¹⁰ W. C. Phalen: Kenova quadrangle. U. S. Geol. Survey, 1912.

¹¹ Joel H. Watkins: Personal letter, 1921.

been altered immediately following eruption into a material somewhat akin to leverrierite. The material swells when put into water and breaks down into a doughy mass with imbedded sand grains. It contains feldspar and other minerals, chiefly leverrierite.

Leverrierite is the mineral that swells in water and breaks up into a doughy mass. The numerous other grains besides leverrierite appear to be angular, broken, embayed crystals, such as are found in volcanic ash, the chief of which, from the optical properties noted, is probably soda orthoclase. In addition to some quartz being present, there is considerable apatite, a very little zircon, and more or less colorless mica. There are also grains that resemble the altered groundmass of a rhyolite and some spherulitic aggregates that are probably chalcedony.

In conclusion, Larsen states that the general character of the purer samples submitted, as well as similarity to the bentonites of the west, which have been shown to have that origin,¹² is that of an altered volcanic ash in which the glass fragments have been changed to leverrierite. The water is lower than in most leverrierites, but it is known that much of the water in leverrierite is loosely held and does not appear to be essential to the mineral.¹³

ANALYSES OF BENTONITE AND LEVERRIERITE

	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
SiO ₂	54.80	54.56	58.88	55.28	51.1	64.00	60.18	47.56
Al ₂ O ₃	22.93	19.97	22.91	24.65	16.1	22.9	26.58	20.57
Fe ₂ O ₃	1.91	.69	.78	.51	4.5	3.1	.....	8.58
FeO	.45	1.28	.86	1.08				
CaO	1.20	1.08	trace	trace	5.2	1.0	.23	2.52
MgO	3.10	5.08	2.36	3.71	3.8	2.0	1.01	.80
P ₂ O ₅	.13	.15	.17	.16	....	....	....	....
F	.11	.13	trace	trace	....	....	....	....
K ₂ O	2.04	4.06	4.30	3.71	1.5	.....	1.23	1.28
Na ₂ O	4.12	1.66	2.42	2.06				
H ₂ O 100°-110° c.	4.58	6.62	3.34	3.44	13.1	....	....	6.65
H ₂ O 150°-160° c.	.68	.48	.26	.52	....	....	....	....
H ₂ O 200°-210° c.	.52	.32	.56	.20	....	7.00	10.26	....
H ₂ O red heat...	3.83	4.52	3.27	4.77	4.0	....	....	10.95

(1) Bentonite from road-cut on Dixie Highway at Singleton, Bedford County, Tennessee; analysis by D. F. Farrar.

(2) Bentonite from High Bridge, Kentucky; analysis by D. F. Farrar.

¹² D. F. Hewett: *Op. cit.*, pp. 196-198.
¹³ Esper Larsen and Edgar T. Wherry: Leverrierite from Colorado. *Jour. Washington Academy of Science*, vol. 7, 1917, pp. 208-217.

(3) Bentonite from Birmingham, Alabama, "Twentieth Street and Red Mountain cut; bentonite, 19 inches"; analysis by D. F. Farrar.

(4) Bentonite from Birmingham, Alabama; "Woodward shaft, east of Readers, at a depth of 1,300 feet; analysis by D. F. Farrar.

(5) Bentonite from eight miles south of Buffalo Gap, South Dakota; Washington Academy of Science, volume 7, 1917, page 580; analysis by Edgar T. Wherry.

(6) Bentonite Laramie basin, Wyoming, Cosgriff's claim.

(7) Bentonite, Laramie basin, Wyoming, Cassa Mining Company.

(8) Leverrierite from Beidel, Colorado; from Washington Academy of Science, volume 7, 1917, page 213; analysis by E. T. Wherry.

A NEW THEORY OF THE FORMATION OF BAUXITE DEPOSITS

Experiments made on bentonite show that when boiled with a five times normal solution of sulphuric acid for five hours the colloidal properties are destroyed; that about 85 per cent of the aluminum oxide goes into solution as aluminum sulphate, along with the alkalies present, but that all the silica except a trace remained undissolved. This fact offers a possible solution to the origin of bauxite, as laboratory experiments show that such a solution of aluminum sulphate is precipitated by a solution of tannic acid after standing for a few days. Deposits of bentonite occurring in contact with pyritiferous rocks would readily have part of their aluminum contents dissolved out by the sulphuric acid in the ground-water, and such a solution of aluminum sulphate, it seems, would be precipitated by natural reducing agents, such as tannic acid or acid peat-forming bacteria, and thus form certain of our present bauxite deposits.

GRAPHIC STUDY OF IGNEOUS ROCK SERIES¹

BY FRANK F. GROUT

(Presented before the Society December 29, 1921)

CONTENTS

	Page
Scope of the paper.....	617
Earlier plots.....	618
Method of plotting.....	618
Constituents to use as coordinates.....	618
Form in which to use them.....	619
General statement.....	619
Silica.....	620
Alkalies.....	620
Selection of data.....	621
The diagrams.....	623
The "trend" of differentiation.....	625
Normal sequences.....	628
Syntexis.....	631
"Primary magma".....	631
The problem.....	631
Evidences from the diagrams.....	632
Degree of uniformity of primary magma.....	633
Summary.....	634
Selected bibliography of rock series.....	635

SCOPE OF PAPER

The increasing number of well studied examples of igneous differentiation and comagmatic regions indicates that a compilation of available data may be suggestive to those who are building petrologic theories on the basis of the idea of differentiation. A fairly satisfactory graph has been found for the concise presentation of the data. On this graph are plotted data for 40 rock-masses in which gradational series can be traced, and about 20 series of less definite connection but strong signs of consanguinity. The several series are widely different, showing that dif-

¹ Manuscript received by the Secretary of the Society January 18, 1922.

ferent factors may dominate differentiation in different cases. If this compilation of scattered data can be kept in mind in building a petrologic theory for one particular case, its object will be amply fulfilled.

EARLIER PLOTS

The diagrammatic presentation of rock series has been attempted by several petrologists.² Few of these plots are so constructed as to show a series of rocks, and only one or two can be satisfactorily used to compare one series with another. Iddings, in discussing rock classification, used a diagram that served for plotting series³ on the basis of silica and the ratio of alkalis to silica. He used the method also for actually plotting as many as five rock series at a time, almost exactly as here planned, but without selecting geologically continuous bodies. Osann has presented two forms of plot,⁴ with triangular coordinates, which might be used to plot actual series, but which he used for a more general discussion of the chemical range of all igneous rocks and their differences from sediments. Several other plots show relationships in a rock series by lines connecting the names on a printed page, but do not make use of any coordinate system.⁵

METHOD OF PLOTTING

CONSTITUENTS TO USE AS COORDINATES

It is, of course, evident to any student of igneous rocks that variations occur in more than two directions. The rocks are mixtures of many components. Any plane diagram must necessarily ignore some of the features of the rocks, and the value of the plot depends on a wise selection of coordinates. Of the several plots on which it is possible to compare one series with another, most are found to use alkalis and silica in some way. The arguments for the use of alkalis and silica are well stated

² Diagrams are reviewed by Iddings in U. S. Geol. Survey Prof. Paper 18 (1903). Other series have been plotted by Adams, *Journal of Geology*, vol. 22, p. 689; by Grout, *Journal of Geology*, vol. 26, p. 622, and by Reid, *Bull. of Dept. of Geology, Univ. of Calif.*, vol. 3, pp. 173-191.

³ J. P. Iddings: *Journal of Geology*, vol. 6, 1898, pp. 92-111 and 219-237.

⁴ A. Osann: *Centralblatt für Min.*, 1913, pp. 481-490. Osann's method of plotting, however, was not as satisfactory for actual rock series as the method selected below.

⁵ L. V. Pirsson: *Tripyramid Mountain, New Hampshire*. *Am. Jour. Sci.*, vol. 31, 1911, p. 430. Pirsson also gave his classes other diagrammatic series to illustrate differentiation.

Weinschenk: *Fundamental principles of petrology*, chapter iv.

Kolderup: *Bergens Museums Aarbog*, No. V, 1896, p. 14.

Rogers (modified from Williams): *The Cortlandt series*. *New York Acad. Sci.*, vol. 21, 1912, p. 58.

by Iddings.⁶ Silica is the most abundant chemical component and that which controls the development of quartz and the several chief igneous minerals; alkalis determine the nature of the feldspars (or feldspathoids), which are the preponderant minerals in most igneous rocks; other constituents sustain, to a considerable extent, a reciprocal relation to these two. The arrangement he found distributed rocks so that unlike rocks are separated. (A possible exception seems to be the placing of anorthosite near basalt and gabbro.)

Ignoring other and theoretical reasons for the use of alkalis,⁷ the last point mentioned assumes an importance beyond any possible theoretical consideration. The fact is that this scheme does give a good distribution; and after a trial of 15 or 20 constituents and combinations, chemical, normative, and modal, the writer found no pair that gave a better plot of the main variations in igneous masses.⁸ There are a few cases like the rocks of Rougemont, Quebec,⁹ in which a change of one-third or more of the mineral content in the series results in little variation in its position in this diagram. On the whole, however, such cases are very rare.

FORM IN WHICH TO USE THEM

General statement.—In using alkalis, Iddings calculated the ratio of alkalis to silica, but explained¹⁰ that the use of direct per cent of alkali would give essentially similar results. Osann used a combination of three constituents recalculated to 100 per cent. Various other men may suggest other methods of using the same data. If any special method had been generally followed, it would be inadvisable to start a new plan; but no such plan is discovered. It has seemed to the writer that another method of arrangement of coordinates might have advantages. It would seem especially desirable to arrange a plot for which data could be roughly estimated from the hand specimen or from measurement by the Rosiwal method. The plot finally adopted shows as abscissas the excess or deficiency of silica in calculation of a norm, and

⁶ J. P. Iddings: U. S. Geol. Survey Prof. Paper 18, 1903, p. 19.

⁷ L. V. Pirsson: Rocks and rock minerals, p. 144, gives a diagram of the variation in composition of rock families, showing smooth curves of variation when arranged in the order of decreasing alkali content. Such curves would not be possible by any other arrangement.

⁸ Potash might be used instead of alkalis, if it proved easier to determine it. Lime (or anorthite) might do as well as potash (or orthoclase), but in general it increases as potash decreases. Iron and magnesia, in the average analyses for rock families, vary together, but do not separate unrelated rocks as well as silica and alkalis. Soda and alumina are almost useless for plotting such a series.

⁹ J. J. O'Neill: Canada Dept. Mines Mem. 43, 1914, p. 88.

¹⁰ Op. cit., p. 20.

as ordinates the direct per cent of alkalis. Any criticism of the use of a norm calculation may, of course, apply to these values, based on the norm.

Silica.—A close estimate of the excess or deficiency of silica can be made from the mode observed or measured even in the field. The subject is, of course, one where care must be used, and due regard for "saturation" and "undersaturation" may be preferred by some petrographers.¹¹ In this country probably more men are familiar with the norm idea than with the idea of saturation. The data for silica are therefore calculated from the norm; or estimated from the mode by the following plan:

1. Quartz is estimated directly as excess silica, corrected only for certain ferromagnesian minerals as below.
2. Deficiencies of silica are indicated by the minerals that do not commonly occur with quartz, as follows:
 - .40 of the olivine present is silica deficiency.¹²
 - .73 of the nephelite present is silica deficiency.
 - .27 of the leucite present is silica deficiency.
 - .18 of the analcite present is silica deficiency.
3. Biotite, hornblende, and augite may occur with quartz or with the minerals just listed and modify the estimate, if they are abundant.
 - .26 of the average biotite is silica deficiency.¹²
 - .07 of the average hornblende is silica deficiency.
 - .05 of the average augite is silica deficiency.

It is freely admitted that biotite, hornblende, and augite appear in equilibrium with quartz in some rocks, but biotite does not appear in the norm and may be calculated as deficient in silica, reducing the indicated excess in quartz rocks. It is noteworthy that in the field the feldspars, which dominate most rocks, are the exactly "saturated" minerals with no excess or deficiency, and are at once eliminated from estimation. This greatly simplifies placing the rock in the chart.

Alkalis.—The sum of soda and potash is plotted directly as ordinates. This may be roughly estimated, from field observations and measurements, as the sum of—

- .15 of the potash feldspar,
- .11 of the sodic feldspar,

¹¹ S. J. Shand: On saturated and unsaturated igneous rocks. *Geol. Mag.*, vol. 10, 1913, p. 508.

¹² The calculation may be illustrated. In the calculation of a norm, when silica is deficient, the first oxides to be reduced to orthosilicates are the ferrous and magnesian oxides, making olivine. If to 10 parts of average olivine 4 parts by weight of silica were added, it would become hypersthene. In any olivine rock, then, it may be said to be necessary to add silica to the amount of .4 of the weight of olivine before additions develop quartz. This .4 of the weight of olivine is the "deficiency" used in plotting.

- .10- of the medium plagioclase,
- .05 of the basic plagioclase,
- .21 of the nephelite,
- .21 of the leucite,
- .10 of the biotite,
- .14 of the analcite,
- .10 of the alkalic pyroxenes, et cetera.

By the use of the microscope or analysis, closer estimates can be made for the alkalies in feldspars, but the several stages of accuracy in no way alter the principle on which the arrangement is made, and field observations may serve to show whether a particular series resembles any here plotted.

It should be noted that the plots here used are so similar in results to plots by Iddings and others, on the basis of silica per cent and ratios of alkali to silica, that no differences in the conclusions can be expected. If it is argued that simple per cents of silica and alkali would be better than either, it may be answered that Washington's compilation of analyses, with accompanying norms, saves practically all calculation of analyzed specimens, and for field estimates the system here adopted is simplest.

SELECTION OF DATA

The data used for the first plot were averages selected from Daly's valuable collection.¹³ Two pegmatites were added. These serve to show differences in a general way, though it has often been emphasized that some particular rock families may range more widely than the average of one family differs from another. The range for any family depends on the strictness with which it is defined.

The data for figure 2 and figure 3 were selected primarily on the basis of their being clear cases of differentiated magmatic *units*, for which quantitative data are available. About 40 bodies have been described in a way to indicate that the different rocks grade into each other and were derived from a single magma. Many are so completely exposed that the nature of the original intrusive magma can be fairly closely estimated—that is, no large part remains deeply concealed and no large part has been eroded and lost. These are naturally the most valuable in a study of differentiation. In a region of disconnected bodies it must always be uncertain whether all phases developed by differentiation have been found. The laws of differentiation must find their surest basis in these

¹³ R. A. Daly: *Igneous rocks and their origin*, pp. 19-36.

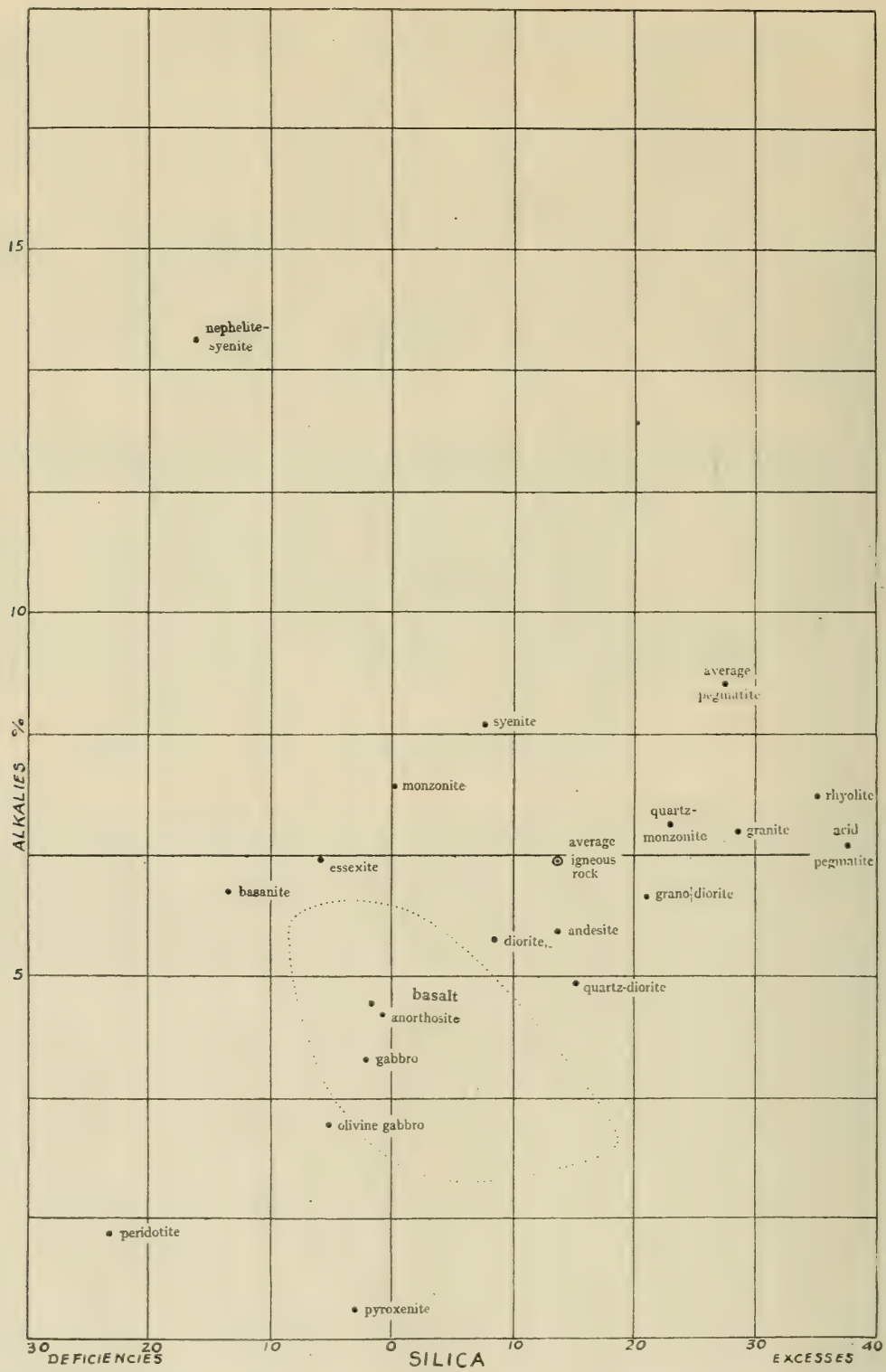


FIGURE 1.—Distribution of standard Rock Families in a Diagram showing Alkalies and Silica

The dotted outline shows the range of composition of the flows from the greater lava fields.

laccoliths and sills that are well dissected, but not so far eroded that any part is wholly lost.

THE DIAGRAMS

Figure 1 shows the location of average rocks of several families. The nephelite syenites extend past the limits of the diagram far beyond the location of the average. Siliceous pegmatities also extend at the opposite corner beyond the limits shown. Most rocks, however, are well placed in the figure. Rocks that are related seem in general to be near together in the plot. The scale is different for the two coordinates, emphasizing the effect of alkalis; but probably this is a proper emphasis and it gives a better arrangement for study.

The acid pegmatite selected was not the most siliceous rock known, but was intended to show a more quartzose rock than typical granite.¹⁴ It was first thought that the average pegmatite would illustrate a siliceous rock, but on averaging the 16 available analyses of granitic pegmatites it was found that, as a group, *pegmatite analyses show more alkalis and less silica than granites*. Probably those siliceous pegmatites so often described are not analyzed, and the alkaline types therefore receive emphasis quite unduly.

Figure 2 shows a few of the larger series plotted in detail. For those series which show a tendency to linear arrangement, lines are drawn on the plots, but some of the series scatter so widely over the plot that a linear connection is not justified.

Figure 3 is based on a similar plotting, but with relatively small amount of data for any district; in some cases only the analyses of the two extremes. For all of these the individual points are here omitted and only the linear tendency shown. A few which showed a tendency to scatter at the end of a series are shown by a line split at the end.

Figure 4 shows a number of supposedly related series of rocks in which the geologic connection is less evident (gradations were not found in continuous exposure), but in which there appears a similar linear trend in the series. In 10 or 15 other districts for which the writer has found a quantitative study of the rocks, there have been suggestions of genetic connection; but, since the various rocks are not connected in outcrop by any gradational series and the diagram shows no pronounced linear trend, they have been omitted from figure 4; they add nothing but the weight

¹⁴ It is found on page 77 of Washington's chemical analyses of igneous rocks, issued as Professional Paper 99 of the United States Geological Survey, 1917.

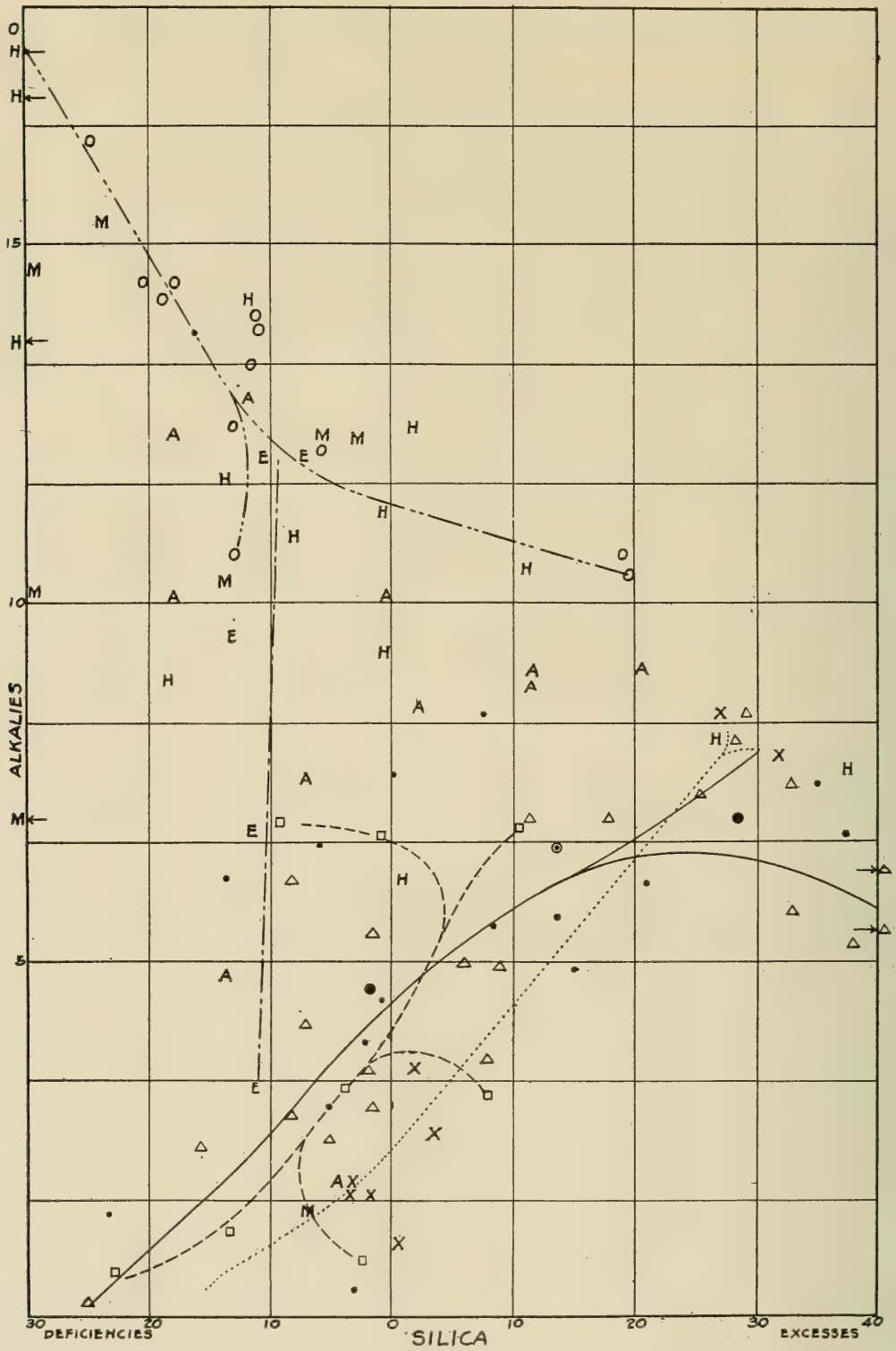


FIGURE 2.—Eight Series of Rocks plotted for each analyzed Specimen

Delta for Duluth, Minnesota, lololith; E and O for Julianehaab, Greenland, two lololiths or batholiths; X for Isle of Skye, lololith or stock; M for Magnet Cove, Arkansas, laccolith; A for Assynt, Scotland, laccolith; H for Haliburton and Bancroft, Ontario, batholith; square for Nordingr  sills. Small spots show standard rocks as in figure 1.

of numbers¹⁵ to the series shown in figure 2. Several other districts are described petrographically as showing similar series, but quantitative data are not available.¹⁶ See the bibliography below.

THE "TREND" OF DIFFERENTIATION

Several remarks on the curves plotted have almost the nature of immediate conclusions.

1. Out of about 40 connected series all but two or three show a linear directional trend in the diagram, with relatively little scattering.¹⁷ This seems to be too strong a proportion to be accidental or the result of the incompleteness of data.

2. The scattering in a series with linear trend seems to occur at the ends of the series rather than in the center. That is, at the basic sub-alkalic end diverse monomineralic rocks separate from a single magma; at the acid alkalic end there seems to be another sort of divergence, with a good deal of variety in the silica and alkali content of the products of one magma. It can not be assumed that during differentiation the liquid magma passed through each stage represented by a rock specimen; but just as the monomineralic basic rocks are precipitates from gabbro magma, so the various acid and alkalic types at the other end probably diverge from some point closer to the average or original magma.

3. Magmas do not have to be of any special or particular composition, to begin with, in order to develop into a differentiated series of rocks. Magmas of the most various sorts have been strongly differentiated. Neither monzonites nor pulaskite nor any common family is to be classed as anchi-eutectic.

4. The trend is in very different directions in different masses, even if the different magmas were of similar compositions. Iddings men-

¹⁵ These districts include the Kola peninsula; the Adirondacks of New York; a series of Hawaiian flows; the absarokite-shoshonite-banakitite series from Yellowstone; the Roman "co-magmatic" region; a group of dikes in Virginia; Port Coldwell, Ontario; the Highwood Mountains as a whole; Kirunavaara; no doubt other series will be found to be omitted. The Christiania rocks shown in the diagram by Iddings, as cited, range widely, but a series from grorudite to tinguaitite can be selected to show a linear arrangement closely analogous to the granite series from Wisconsin.

¹⁶ The flows from many volcanoes show partial series between gabbro and rhyolite, and a few show more alkalic types. The rocks of Tasmania range from pyroxenite to nephelite syenite with no granite. Series of rocks have been described from Bozeman, Montana, from the Black Forest, from East Griqualand, etcetera, but these can hardly be plotted.

¹⁷ By "linear" it is not the intention to suggest straight lines, but a lack of scattering. Harker has used the term for straight lines; see *Journal of Geology*, vol. 8, p. 391.

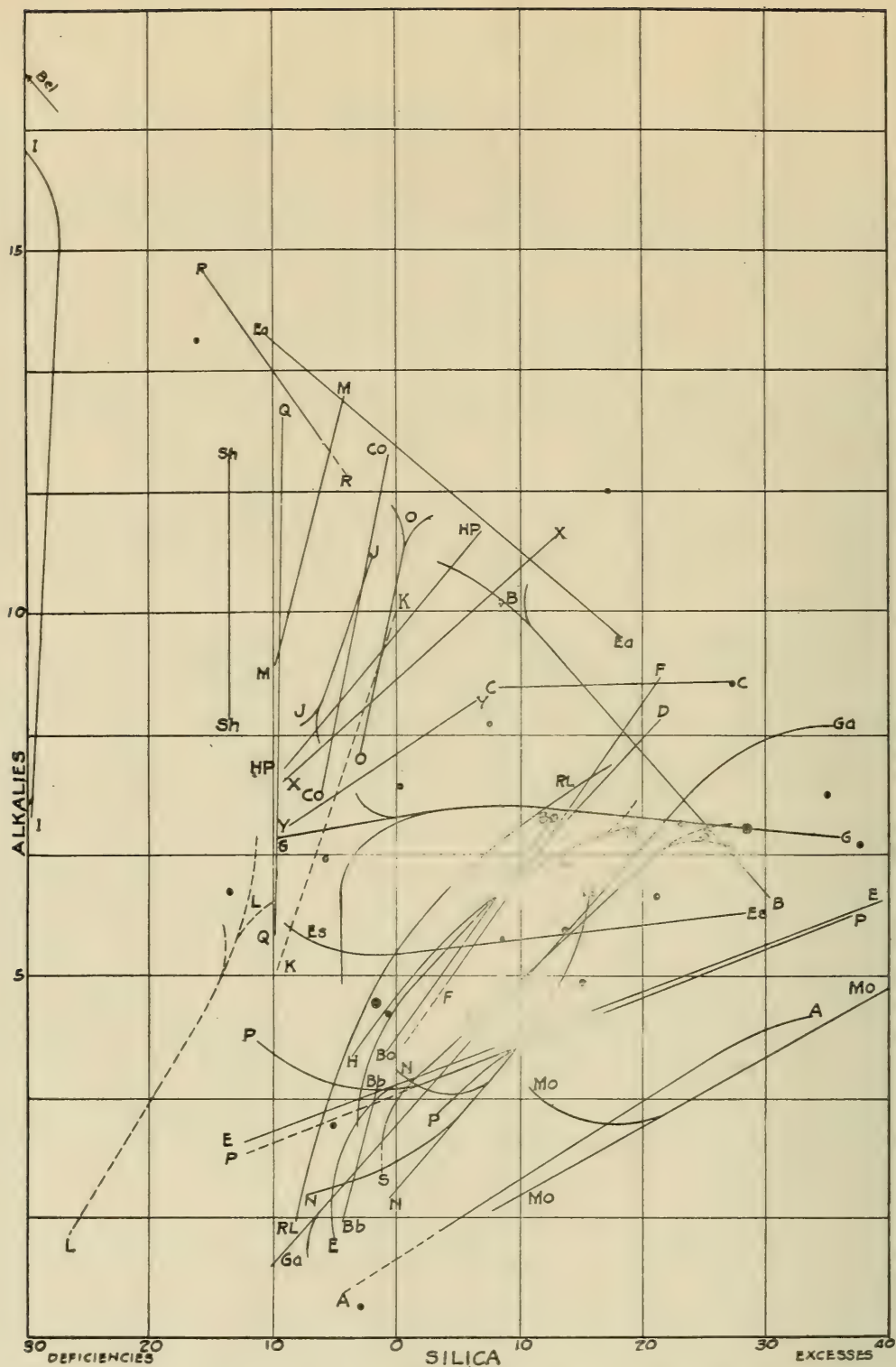


FIGURE 3.—Rock Series showing Gradations in single Masses

Broken lines used for calculated data; full lines for analytical data. Split lines show scattering, but do not in all cases extend to all the points plotted. Small spots show standard rocks, as in figure 1.

A = Maryland (northeastern part); B = Belknap Mountains, New Hampshire; Bb = Brandenberget, Gran, Norway; Bel = Beloeil (Saint Hilaire), Quebec (used data for a single one of the two intrusions); Bo = Mount Bohemia, Michigan; C = Castle Mountains, Montana; Co = Coryell, British Columbia; D = Saint David's Head, Wales (author favors heterogeneous intrusion); E = East Sooke, Vancouver; Ea = Essex, Massachusetts (alkaline body); Es = Essex, Massachusetts (subalkaline body); F = Carrock Fell, England (author favors syntaxis); G = Gowanda, Ontario; Ga = Garabal Hill, Scotland; H = Haystack Mountain, Montana; HP = Highwood Peak, Montana (a single mass in the Highwood Mountains; see figure 4); I = Ice River, British Columbia; J = Mount Johnson, Quebec; K = Huk, Norway (rough analyses only); L = Lugar, Scotland (calculated from measured thin sections); M = Middle Peak, Montana; Mo = Moyie (Purcell), British Columbia (author favors syntaxis); N = New Jersey (Palisades diabase); O = Mount Shefford, Quebec; P = Preston, Connecticut; Q = Square Butte, Montana; R = Red Hill, New Hampshire; RL = Rocky Islet, Rainy Lake, Ontario; S = Sudbury, Ontario; Sh = Shonkin Sag, Montana; X = Bear Paw Peak, Montana; Y = Yogo Peak, Montana.

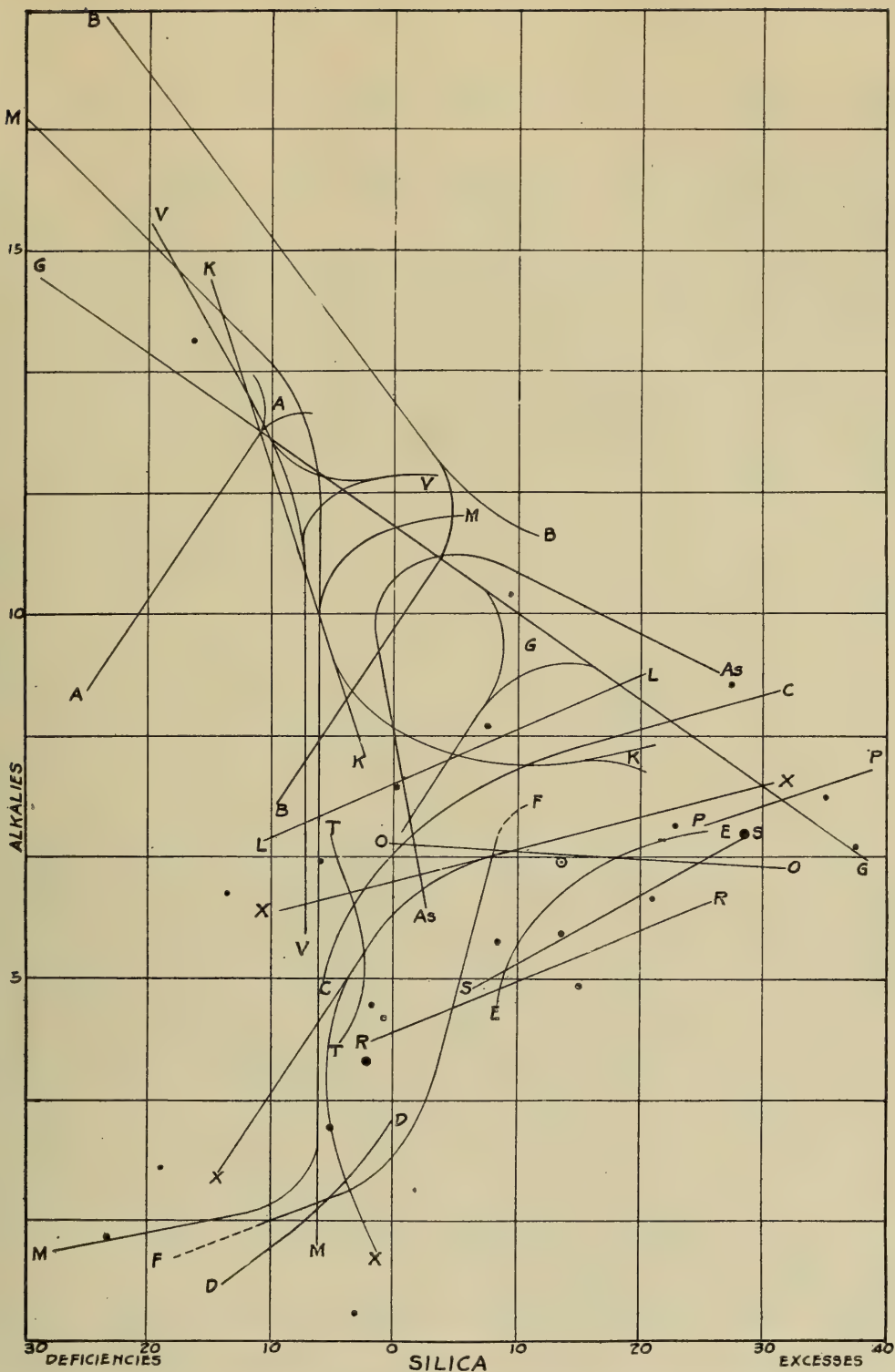


FIGURE 4.—Series supposed to be related genetically, but not showing clear Gradations in the whole Range of Specimens

Small spots show standard rocks, as in figure 1.

A = Almunge, Sweden (set plotted probably incomplete; Bowen (op. cit., pages 63-4) says these are transitional to granite); As = Ascutey Mountain, Vermont (whole series here; only a slight variation appears in a single stock (diorite); (author favors syntaxis); B = Bearpaw Mountains, Montana (whole series here; one mass shown in figure 3); C = Castle Mountains, Montana (whole series here; one mass shown in figure 3); D = Central Wisconsin (diorite); E = Electric Peak, Yellowstone Park; F = Crystal Falls, Michigan (transitions in single mass are known, but the analyses are not all from such a single mass); G = Central Wisconsin (granite); K = Kruger, British Columbia (spreads widely over the plot); L = Little Belt Mountains, Montana (whole series here; Yogo Peak separately in figure 3); M = Monteregian Hills, Quebec (whole series here; several single masses in figure 3); O = Old Hampshire County, Massachusetts; P = Pyramid Peak, California; R = Rimmel, British Columbia; S = Siesse, British Columbia; T = Tripyramid Mountain, New Hampshire (outcrops include an aplite with some quartz, not analyzed); V = Cuttingsville, Vermont; X = Cortlandt, New York.

tioned this feature years ago,¹⁸ and similar ideas were stated by Cross¹⁹ and by Pirsson.²⁰

5. There is a rough suggestion of divergence, or radiation, in the lines of figure 3, from the area of low alkalis and low silica, to all the rest of the areas, but there are several pronounced exceptions, and it can not be assumed that the approximate center of the radial lines was "primary magma." In fact, after a general glance at figure 3, two or more centers of radiation are almost as clear as one. Probably none is especially significant.

6. The alkaline rocks are approached by series from either gabbro or granite. Numerous good examples can be selected from the diagrams and need not be mentioned specifically.

Two or three regions furnish a series ranging from nephelite syenite toward *both* gabbro and granite. No series, however, furnishes data for a connected series from gabbro to nephelite rocks by way of granite.

NORMAL SEQUENCES

Igneous rock series have long been known to be of several sorts, and Rosenbusch has described three "magmatic series"²¹—the granito-dioritic, gabbro-periodotitic, and foyaitic-theralitic. Cross has criticised the series as no more "natural series" than the series connecting one of them to the other. Pirsson shows alkalic and sub-alkalic series with monzonite between and suggests that crossing or connecting series are possible in various directions.²² Bowen gives several series and selects one as a "normal line of descent,"²³ though he presents this normal series with some hesitation because of its rigidity, and offers some alternatives. While these several schemes are based on considerable field and laboratory data, it is planned here to show the relation of theoretical series to the actual series now known.

Many of the actual series plotted fall along the line from the general gabbro area to the general granite area. This is clearly a "normal"

¹⁸ J. P. Iddings: Absarokite-shoshonite-banakite series. Jour. Geology, vol. 3, pp. 955-959; see also vol. 6, p. 107.

¹⁹ W. Cross: The natural classification of igneous rocks. Quart. Jour. Geol. Soc., vol. 66, 1910, p. 481.

²⁰ L. V. Pirsson: Petrography of Tripyramid Mountain. Am. Jour. Sci., vol. 31, 1911, p. 430.

²¹ H. Rosenbusch: Mikroskopische Physiographie. Massige Gesteine, 4th ed., vol. 2, pt. 1, 1908, p. 13.

²² L. V. Pirsson: Petrography of Tripyramid Mountain. Am. Jour. Sci., vol. 31, 1911, p. 430.

²³ N. L. Bowen: Evolution of igneous rocks. Jour. Geol. Supplement, 1915, p. 75.

sequence, in the sense that many occurrences illustrate it. There is not, however, any great preponderance of such well studied series gabbro to granite over series between the other extremes. If the series from basalt to granite is the main result of wholesale differentiation in nature, the process has apparently tended to obscure itself, probably because the large size of the resulting masses makes it difficult to follow the gradation to an extreme. The emphasis on this series in many published discussion is based more on the abundance of the extreme products, basalt and granite, than the abundant illustrations of the gradational series. Any series which will explain the relations of our commonest rocks is especially noteworthy.

The lines on the plots run gabbro—diorite—granodiorite—granite. The granites show a good deal of variation from siliceous to alkalic types, both being well illustrated. Several of the series extend, at the basic end, to peridotite. These make it evident that there is no real division between Rosenbusch's two main series.

Bowen does not stop his series at granite, but extends it *through* granites to alkaline types. In this he goes farther than the other writers just mentioned in connecting rocks in a supposed genetic series. The series from granite to alkaline types is clear enough, but the argument that the normal descent runs from gabbro to granite to alkaline types is based on the broader argument that practically all the granites are derived from basaltic magma. No single mass of igneous rock seems to show such an extended series. Furthermore, a series of this sort plotted on figure 1 would give such a sharp change in direction as to be very surprising. Bowen may have appreciated this, for he suggests that the control of the process is modified at this stage by the increase in the amount of water in the magma.

The clear suggestions to be derived from the diagrams are, first, that the known series *do not run* continuously from gabbro to granite to nephelite syenite; and, second, that if the absence of such a series is due to incomplete exposures or analyses, the process of differentiation changes most remarkably in passing the stage of granite. The curve shows too sharp a turn to be suggestive of a continuous process.

Bowen's "variant" series²⁴ only emphasizes the difficulty arising from an attempt to follow his theoretical series through the diagram. He supposes in this case that the magma passes from syenite to granite to alkaline types. If the rock names mentioned in such a series are average types, the sequence when plotted seems wholly improbable. Attention

²⁴ Op. cit., p. 77.

is called to it simply to stimulate careful field observations as to whether the series really exists; and to suggest that the series is more likely to have syenite *between* granite and nephelite syenite than to run from syenite to granite to alkaline types. This is the series shown by Pirsson²⁵ in a generalized diagram, and Bowen himself speaks of the occurrence of alkaline granites and syenites between granites and nephelite syenites.²⁶ His tabulated series, however, does not specify the subalkaline syenites which must be the only possible syenites that could grade through granite to alkaline rocks.

The diagrams show several good examples of a series from gabbro to essexite to nephelite syenite. These show that Rosenbusch's several series were not really distinct. It is also rather different from any series suggested as likely by Pirsson, on the assumption of a primary magma of "intermediate" composition, such as monzonite, or the "average igneous rock." The sequence is mentioned by Bowen as a third possible sequence,²⁷ but even in this case he postulates a development of nephelite *only by the "activity" of water in developing quartz rocks.*

The idea that nephelite develops only by an equilibrium which allows the settling or separation of quartz is certainly not favored by the diagrams. Almost one-fourth of the series show a transition from olivine rocks to nephelite rocks without any development of quartz rocks. Still others show so little quartz that it can not account for the nephelite found. This objection, to be sure, is not a rigid one, for it may be that the magma was differentiated and quartz separated before intrusion into the present chamber. The prominent examples, however, indicate some process of development of nephelite besides the separation of quartz.

A final suggestion from the diagrams is based on the evident tendency of several series to scattering at each end. The scattering at the gabbro end of the "normal" series is attributed to the accumulation of crystals from a gabbro magma. The scattering at the acid and alkaline ends has not been emphasized, but seems to be rather a conspicuous feature. Probably the best sequence for the differentiation of "primary basaltic" magma into both granite and nephelite syenite would be a series leading first toward syenite; from a syenitic magma the separation of granite might leave nephelite syenite still liquid. Such a series would not properly be *through granite* to nephelite syenite, but *through syenite* to both nephelite syenite and granite. And it is to be emphasized that data for such a series are not yet available, while there are some 50 or more other well-

²⁵ L. V. Pirsson: Rocks and rock minerals, p. 144.

²⁶ Op. cit., p. 57.

²⁷ Op. cit., pp. 57 and 78.

studied series. If any such series can be studied it will be a valuable addition to the list of differentiated regions.²⁸

SYNTEXIS

Since the normal sequence of rocks from gabbro to granite can be so well explained by crystallization from basaltic magma, the argument for syntexis has recently been based more largely on the occurrence of alkaline rocks, for which crystal settling seems a less satisfactory explanation. Daly and Foye argue for the effect of basic sediments as controlling this change from the main part of the normal series to an alkaline type.²⁹

The nephelite syenites scatter widely in the diagrams, but it may be remarked that practically every series including nephelite syenite passes very close to the average nephelite syenite. Some series from nephelite syenite to subalkalic rocks run to gabbro and some to granite. Is it possible that the assimilation of sediments is so well regulated by nature as to give the same product, nephelite syenite, no matter what the composition of magma to start with? In case of granite, the assimilated material would desilicate the magma and increase the alkalis a little without leaving much lime in the desilicated magma. In the case of gabbro, the alkali content would need to be enormously increased and ferromagnesian minerals eliminated. The uniformity of product is hardly to be expected from assimilation without a more definite control by differentiation. And if differentiation is the chief control, it seems sufficient to explain the results without any important relation to assimilation.

PRIMARY MAGMA

THE PROBLEM

As recently as 1911, Loewinson-Lessing presented somewhat elaborate arguments for at least two primary earth magmas, basaltic and granitic.³⁰ This was in continuation of similar theories which had been argued for

²⁸ Probably the best approach to such an example at present is the Haliburton-Bancroft area, where the nephelite rock is related to both essexite and granite; but even there no connection has been shown between granite and a basaltic magma. In central Wisconsin, where series have been found including gabbro, granite, and alkaline types, the geologic connection is more remote and gradations have not been reported. With the present data, shown in the D and G lines of figure 4, it would be hard to predict where the lines should be connected.

²⁹ R. A. Daly: *Igneous rocks and their origin*, p. 414.

W. G. Foye: *Nephelite syenites of Haliburton County, Ontario*. *Am. Jour. Sci.*, vol. 40, 1915, pp. 428-436.

³⁰ F. Loewinson-Lessing: *Origin of igneous rocks*. *Geol. Mag.*, vol. 8, 1911, pp. 248-297.

sixty years or more, but which were coming into disfavor as the idea of differentiation came to be accepted as explaining the variety in igneous rocks.³¹ Since then Daly³² and Bowen³³ have each presented strong arguments for considering all primary magmas as basaltic. Meanwhile, others have been influenced, probably by the calculation of the "average igneous rock,"³⁴ to consider magma of intermediate composition as the most abundant, if not the only primary magma.³⁵ Several petrographers still write as if they considered the primary magma in some regions very different from that in others. The diagrams furnish data that are, to say the least, very suggestive.

EVIDENCES FROM THE DIAGRAMS

The simple fact of the occurrence of a differentiated series does not necessitate starting with basaltic magma nor any of the "normal" series of derivatives of basalt toward granite. Using the best estimates that could be found or made from the published data, the writer has tabulated the compositions of the magmas *as intruded* into the chambers where differentiation has been strongly active and the results well exposed. The magmas show a wide range—from olivine gabbro as at Preston to granophyr diabase as at Sudbury; from quartz syenite as at Assynt to nephelite syenite as at Ice River, with branches to teschenite as at Lugar, Scotland, and to essexite as at Saint Hilaire. Many show no phase approaching basalt, but all are sharply differentiated.

The course of differentiation of several bodies of magma that are not basaltic as intruded is not in a direction to indicate that the process began with basalt. To be sure, some series grade from intermediate rocks to granite, like those at Pyramid Peak and the Slesse batholith, and some grade from alkaline basalts to yet more alkaline types, like the Square Butte series, all assuming a trend on the diagram as if the primary magma had been basaltic. Others are so different in trend as to suggest no relation to basalt. The Castle Mountain stock, and the series from Belknap Mountain, and that from Almunge give curves that do not pass near basalt, and have a trend that is certainly not to be expected, if the primary magma was average basalt.

³¹ J. P. Iddings: *Igneous rocks*, vol. 1, gives a review of the development of these theories.

³² R. A. Daly: *Igneous rocks and their origin*, pp. 264-5 and p. 458.

³³ N. L. Bowen: *Op. cit.*, pp. 66-73.

³⁴ The latest calculation, referring to others, is by H. S. Washington. *Chemistry of the earth's crust*. Jour. Franklin Inst., vol. 190, 1920, p. 773.

³⁵ Monzonite magma is taken as a logical start, by Pirsson and Cross. See *Am. Jour. Sci.*, vol. 31, p. 430 (1911). Diorite is considered most reasonable by Campbell. See the October, 1920, meeting of the Institution of Mining and Metallurgy

It may be argued that the intrusion of a partly differentiated magma separating it from its original basaltic products would be accompanied by a change of pressure and water content, et cetera, so that the course of differentiation might be changed. Intrusion, however, would hardly be expected to normally increase the water content, and some of the series plotted grade toward alkaline types in such a way as to indicate a high content of mineralizers. As a whole, therefore, the diagrams are less indicative than other lines of evidence that basalt was "the primary magma."

DEGREE OF UNIFORMITY OF PRIMARY MAGMA ³⁶

There are many reasons for the prevalent idea that primary magma is homogeneous. Under the theory of a molten earth, or even a molten surface layer, there would be abundant opportunity for general stirring and mixing to promote uniformity. Within any large body of magma, convection and diffusion tend toward homogeneity. It is now popular to emphasize the similarity of magmas and solutions, and one of the textbook characteristics of solution is the tendency to become homogeneous.

The field evidences are also strong.³⁷ Basalt penetrates the upper earth without associated acid rocks in so many cases and with such uniformity of composition that it can not be considered as freshly differentiated from magma of intermediate composition. The differentiation of basalts seems to be related to the size of the mass, granites being a sign of large masses; and the bodies of acid rocks, the only rocks of greater known volume than basalts, are very large and their lower phases concealed. Finally, and perhaps most significant of all, is the observation that basalt is the most widespread in time and space of all the lavas that seem to have come rapidly from the regions of magma generation to their solidification, and the chief rock in all extensive lava fields.

Arguments against uniformly basaltic magma (cited above) are found in the scarcity of intermediate rocks; the occurrence of some intermediate rocks as cores related to differentiated flows; the difference in pre-Cambrian and post-Cambrian magmas; and some new calculations based on isostasy.

Whatever the basis for the conclusion, both the authors, arguing for basaltic magma as "primary," refer to its "uniformity."

³⁶ The uniformity of composition of a *rock family* depends largely on the strictness of definition of the family. Basalt is very variable if it includes rocks with and without feldspathoids and with and without olivine. As an example of a more strict definition, granodiorites are defined by Lindgren with relatively narrow limits. No one, however, would suggest that granodiorite must be a primary magma because of its uniformity.

³⁷ R. A. Daly: *Op. cit.*, pp. 164-165.

Assuming that the great flows from fissure eruptions give us our best approximation to primary magma, Daly finds probably 95 per cent are basalts,³⁸ though the total areas of andesites in the earth's exposures are greater than those of basalts. The actual data³⁹ for such basalts were plotted and enclosed in the dotted outline in figure 1.

They are seen to range more widely than average basalt differs from average igneous rock. Numerous other basalts range yet more widely, but are smaller in bulk and less certain to be "primary" magma. The range is probably greater than one would expect after reading of the "uniformity" of primary magma.

Furthermore, taking these great flows as the best illustrative material, it is noteworthy that the average is not olivinitic, but has normative quartz. Most petrographers, assigning normal basalt the mineral composition of an olivine gabbro, think of its chemical composition as also near that of olivine gabbro. On the contrary, these great basalt eruptives are more siliceous than even an olivine-free gabbro, and range both above and below average gabbro in amount of alkalies.

It may be seen that, if primary basalt varies as these samples indicate, some are very close to diorite. Those petrographers who have decided that dioritic magma was primary in certain regions may be no more in error than those who would claim average basalt for all regions. As Pirsson stated it,⁴⁰ "whether the magma shell of the molten earth (supposing there ever was such a thing) was ever homogeneous or not . . . is purely an academic question . . . the magmas underlying the crust are different now in different regions." The variation in alkalies is marked and the excess or deficiency of silica may reach 10 per cent.

SUMMARY

The process of differentiation is not to be outlined in one sequence, nor even in two. There are many diverse series. The nature of the differ-

³⁸ Op. cit., p. 120.

³⁹ Analyses obtained as follows:

Deccan, rough analysis. *Geol. Mag.*, vol. 2, 1905, p. 21.

Washington State. U. S. Geol. Survey Folio 106, p. 6.

Lake Superior Archean; average by Zapffe. *Econ. Geol.*, vol. 2, p. 149.

Idaho, Columbia lava. U. S. Geol. Survey Folio 106, p. 8.

Iceland. U. S. Geol. Survey Prof. Paper 99, p. 649.

Lake Superior Keweenawan. Average of the best given in *Jour. Geol.*, vol. 18, pp. 644-650.

New Jersey. Average of those in New Jersey Geol. Survey Ann. Rept. 1907, p. 159.

Idaho, Snake River. U. S. Geol. Survey Bull. 199, p. 87.

Purcell lavas, B. C. Rept. of Chief Astronomer, 1910, Appendix No. 6, p. 209.

British Isles. Average between dolerite described in *Geol. Mag.*, vol. 2, 1905, p. 21, and the flows in Skye, *Mem. of Geol. Survey of United Kingdom*, 1904.

⁴⁰ *Am. Jour. Sci.*, vol. 20, 1905, p. 47.

entiation in 40 cases is shown by diagrams based on alkalies and silica. Magmas do not have to be of any particular composition, to begin with, in order to develop into a differentiated series. The *trend* or direction of variation is very different in different localities, even when magmas are similar. As noted many years ago, rocks of great similarity may develop from magmas of very different composition as intruded.

Nearly all the notably alkaline rock-masses have some phase near average nephelite syenite, whether related to gabbro or to granite. It can hardly be assumed that assimilation or syntexis is the dominant factor in producing such a uniform nephelite syenite from such diverse original magmas.

Primary magma probably approaches average basalt, but varies so widely that it may be truly dioritic or highly alkaline in extreme cases.

SELECTED BIBLIOGRAPHY OF ROCK SERIES

A. Gradational Series

- Julianehaab*.—N. V. Ussing: Geology of the country around Julianehaab, Greenland. Copenhagen.
- Skye*.—Alfred Harker: Tertiary igneous rocks of Skye. Memoirs of the Geological Survey of United Kingdom, 1904.
- Magnet Cove*.—H. S. Washington: The foyelite-ijolite series of Magnet Cove. Journal of Geology, volume 9, 1901, pages 645-670.
- Nordingrå*.—J. M. Sobral: Geology of the Nordingrå region. Dissertation, Upsala, 1913.
- Haliburton*.—F. D. Adams and A. E. Barlow; Geology of the Haliburton and Bancroft areas. Canada Department of Mines, Geological Survey Memoir 6, 1910.
- Duluth*.—Frank F. Grout: A type of igneous differentiation. Journal of Geology, volume 26, 1918, pages 626-658.
- Assynt*.—S. J. Shand: On borolanite and its associates in Assynt. Transactions of the Geological Society of Edinburgh, volume 9, 1910, pages 376-416 (with analyses by Gemmel, pages 417-419).
- Shonkin Sag, Square Butte, Highwood Peak, Middle Peak*.—L. V. Pirsson: The igneous rocks of the Highwood Mountains, Montana. U. S. Geological Survey Bulletin 237, 1905.
- Sudbury*.—A. P. Coleman: The nickel industry. Canada Department of Mines, Mines Branch, number 170, 1913.
- Essex County*.—C. H. Clapp: Geology of the igneous rocks of Essex County, Massachusetts. U. S. Geological Survey Bulletin 704, 1921.
- Purcell*.—R. A. Daly: Geology of North American Cordillera at the 49th parallel. Report of Chief Astronomer (Ottawa), number 6, 1913, pages 221-255.
- Haystack Mountain*.—W. H. Emmons: Geology of the Haystack stock, Montana. Journal of Geology, volume 16, 1908, pages 193-229.

- Carrock Fell*.—Quarterly Journal of the Geological Society, volume 50, pages 311-337, and volume 51, 1894-5, pages 125-148.
- Palisades Diabase*.—J. V. Lewis: Petrography of the Newark igneous rocks of New Jersey. New Jersey Geological Survey Annual Report, 1907, pages 121-132.
- Mt. Johnson*.—F. D. Adams: The Montereian Hills. Journal of Geology, volume 11, 1903, pages 239-282.
- Beloeil*.—J. J. O'Neill: St. Hilaire (Beloeil) and Rougemont Mountains, Quebec. Canada Department of Mines, Memoir 43, 1914, pages 40-48.
- Ice River*.—J. A. Allen: Geology of the Field map-area, British Columbia and Alberta. Canada Department of Mines, Memoir 55, 1914, pages 121-193.
- Huk*.—J. H. L. Vogt: Formation of iron-ore deposits in Sweden and Norway. Transactions of the Geological Society in Stockholm, volume 13, 1891, pages 476-536.
- Lugar*.—G. W. Tyrrell: Alkaline igneous rocks of the west of Scotland. Geological Magazine, volume 49, 1912, pages 69-80 and 120-131.
- Mt. Bohemia*.—F. E. Wright: Intrusive rocks of Mt. Bohemia, Michigan. Michigan Geological Survey Annual Report, 1908, pages 361-394.
- Brandenberg (Gran)*.—W. C. Brögger: Basic eruptive rocks of Gran. Quarterly Journal of the Geological Society, volume 50, 1894, pages 15-38.
- Preston*.—G. F. Loughlin: The gabbros and associated rocks at Preston, Connecticut. U. S. Geological Survey Bulletin 492, 1912.
- Belknap Mountains*.—L. V. Pirsson and H. S. Washington: Petrography of the Belknap Mountains. American Journal of Science, volume 22, 1906, pages 439-457 and 493-514.
- Castle Mountains*.—W. H. Weed and L. V. Pirsson: Geology of the Castle Mountains mining district, Montana. U. S. Geological Survey Bulletin 139, 1896.
- Beaver Creek Core*.—W. H. Weed and L. V. Pirsson: The Bearpaw Mountains of Montana. American Journal of Science, volume 1, 1896, pages 351-362.
- Coryell*.—R. A. Daly: Geology of North American Cordillera at the 49th parallel. Report of the Chief Astronomer (Ottawa) Appendix number 6, 1913, pages 358-370.
- Gowganda*.—N. L. Bowen: Diabase and granophyr of the Gowganda Lake district. Journal of Geology, volume 18, 1910, pages 658-674; and W. H. Collins, Canada Department of Mines, Geological Survey Memoir 33.
- East Sooke*.—H. C. Cooke: Gabbros of East Sooke and Rocky Point. Canada Department of Mines, Museum Bulletin 30, 1919.
- Red Hill*.—L. V. Pirsson and H. S. Washington: Geology of Red Hill, New Hampshire. American Journal of Science, volume 23, 1907, pages 257-276, and later.
- Garabal Hill*.—J. R. Dakyns and J. J. H. Teall: Plutonic rocks of Garabal Hill and Meall Breac. Quarterly Journal of the Geological Society, volume 48, 1892, pages 104-121.
- St. David's Head*.—J. V. Elsdon: The St. David's Head rock-series. Quarterly Journal of the Geological Society, volume 64, 1908, pages 273-296.
- Yogo Peak*.—L. V. Pirsson: Igneous rocks of little Belt Mountains. U. S. Geological Survey Annual Report 20, part 3, 1900, pages 471-488.

- Mt. Shefford*.—J. A. Dresser: On the petrography of Shefford Mountain. *American Geologist*, volume 28, 1901, pages 203-213.
- Rocky Islet*.—A. C. Lawson: The Archean geology of Rainy Lake. Canada Department of Mines, *Memoir* 40, 1913, pages 82-91.
- Maryland*.—A. G. Leonard: Basic rocks of northeastern Maryland and their relation to the granite. *American Geologist*, volume 28, 1901, pages 135-175.

B. Not so clearly Gradational

- Central Wisconsin*.—Samuel Weidman: The geology of north central Wisconsin. *Wisconsin Geological and Natural Historical Survey Bulletin* 16, 1907.
- Cortlandt*.—G. S. Rogers: Geology of the Cortlandt series, etcetera. *Annals of New York Academy of Sciences*, volume 21, 1911, pages 11-86.
- Tripyramid Mountain*.—L. V. Pirsson: The petrography of Tripyramid Mountain. *American Journal of Science*, volume 31, 1911, pages 405-431.
- Ascutney Mountain*.—R. A. Daly: The geology of Ascutney Mountain, Vermont. *U. S. Geological Survey Bulletin* 209, 1903.
- Pyramid Peak*.—Waldemar Lindgren: The granitic rocks of the Pyramid Peak district. *American Journal of Science*, volume 3, 1897, pages 301-314.
- Almunge*.—P. D. Quensel: The alkaline rocks of Almunge. *Geological Institute Upsala Bulletin*, volume 12, page 157.
- Bearpaw Mountains*.—W. H. Weed and L. V. Pirsson: The Bearpaw Mountains of Montana. *American Journal of Science*, volume 1, 1896, pages 351-362.
- Little Belt Mountains*.—L. V. Pirsson: Igneous rocks of Little Belt Mountains. *U. S. Geological Survey Annual Report* 20, part 3, 1900, pages 257-581.
- Cuttingsville*.—J. W. Eggleston: Eruptive rocks at Cuttingsville, Vermont. *American Journal of Science*, volume 45, 1918, pages 377-410.
- Monteregian Hills*.—F. D. Adams: *Journal of Geology*, volume 11, 1903, pages 271-282.
- J. A. Dresser, *American Geologist*, volume 28, 1901, pages 209-213.
- J. A. Dresser, *American Journal of Science*, volume 17, 1914, page 354.
- J. J. O'Neill, *Canada Geological Survey Memoir* 43, 1914.
- Electric Peak*.—J. P. Iddings: The igneous rocks of Electric Peak and Sepulchre Mountain. *U. S. Geological Survey Monograph* 32, part 2, 1899, pages 89-142.
- Kruger*.—R. A. Daly: Geology of the North American Cordillera at the 49th parallel. *Report of Chief Astronomer (Ottawa)*, Appendix number 6, 1913, pages 450-472.
- Slesse*.—Ditto, pages 533-538.
- Rommel*.—Ditto, pages 443-448 and 472.
- Crystal Falls*.—J. M. Clements: A Study of some examples of rock variation. *Journal of Geology*, volume 6, 1898, pages 372-392.
- Old Hampshire County*.—B. K. Emerson: The geology of Old Hampshire County, Massachusetts. *U. S. Geological Survey Monograph* 29, 1898, pages 307, 349.
- Adirondacks*.—New York State Museum *Bulletins* 115, 119, and 145.

Roman region.—H. S. Washington: The Roman comagmatic region. Carnegie Institute Publication, 1906.

Central western Virginia.—T. L. Watson and J. H. Cline: Petrology of a series of dikes. Bulletin of the Geological Society of America, volume 24, 1913, pages 301-334.

Christiania.—W. C. Brögger: Die Eruptivgesteine des Kristianiagebietes. 1894.

Kiruna.—P. Geijer: Geology of Kiruna District. 1910.

Kola.—Ramsey and Hackman: Fennia, volume 11, number 2, 1894; and B. Hackman: Commercial Geology of Finland, number 15, 1905.

Port Coldwell.—H. L. Kerr: Nephelite syenites of Port Coldwell. Nineteenth Annual Report of Ontario Bureau of Mines, part I, 1910, pages 209-232.

Yellowstone.—J. P. Iddings: Alsarokite-shoshonite-banakite series. Journal of Geology, volume 3, 1895, pages 935-959.

Mauna Kea.—R. A. Daly: Magmatic differentiation in Hawaii. Journal of Geology, volume 19, 1911, pages 289-316.

Central Montana.—L. V. Pirsson: The petrographic province of central Montana. American Journal of Science, volume 20, 1905, pages 35-49.

CORRELATION OF THE JURASSIC FORMATIONS OF
WESTERN CUBA ¹

BY BARNUM BROWN AND MARJORIE O'CONNELL

(Presented before the Society December 30, 1921)

CONTENTS

	Page
Introduction.....	639
History of investigations.....	640
Typical sections of the Jurassic in the Province of Pinar del Rio.	642
General statement.....	643
Candelaria section.....	644
San Cristobal sections.....	645
Sections near San Diego de los Baños.....	646
Viñales sections.....	646
General summary of field relations and their significance.....	651
Correlation of the Jurassic of Cuba and Mexico.....	653
Correlation of the Jurassic of Cuba and Europe.....	656
Classification of Middle and Upper Jurassic of western Cuba and southern Europe.....	656
Comparison of Cuban succession with European standard.....	660
Summary.....	663

INTRODUCTION

This paper constitutes a general summary of the field and laboratory work on the Jurassic of Cuba thus far completed by the authors. It is based on personal studies made by Mr. Brown in Cuba during five journeys, covering eleven months of field work and exploration, in those provinces west of Camaguey, and on the results obtained by Miss O'Connell in working up the collections of fossils, the identification of which has made possible the determination of the succession of the paleontological zones and the correlation of the strata with synchronous ones in Mexico and Europe. The Jurassic fauna, consisting mainly of ammonites, has been described in a separate memoir, to be published at a

¹ Manuscript received by the Secretary of the Society February 6, 1922.

later date, but the broad stratigraphic results may here be set forth in advance of the paleontological details.

HISTORY OF INVESTIGATIONS

Since the beginning of the nineteenth century, when Alexander von Humboldt² visited Cuba and reported the existence of Jurassic rocks in the western part of the island, there have been numerous, for the most part unsubstantiated, rumors of the presence of the Jurassic, but paleontological evidence has been lacking until recently. In 1881 De Castro³ called attention to the occurrence of ammonites in the Province of Pinar del Rio, and referred them to the Jurassic without, however, illustrating any or mentioning any by name. De Castro and Don Pedro Salterain, in 1884, published a geological formation map of Cuba, a part of which was revised and added to in 1916 for the detailed map of the Province of Pinar del Rio.

Even as recently as two decades ago, knowledge of Cuban Jurassic was very meager. "The Report on a Geological Reconnaissance of Cuba," made under the direction of General Leonard Wood, by C. Willard Hayes, T. Wayland Vaughan, and A. C. Spencer, geologists, contains the following statement:

*"Jurassic?—Strata of Jurassic age have been reported from Cuba and the Isle of Pines since the time of Humboldt. The determination is based upon paleontologic evidence which, when examined critically, proves to be insufficient, and we merely make a note here that limestones occurring in the Provinces of Havana and Pinar del Rio have been referred to a Jurassic horizon."*⁴

To Dr. Carlos de la Torre, professor in the University of Havana, belongs the credit of having brought the Jurassic ammonites of Cuba to scientific notice. In 1909 he published a preliminary statement in regard to collections which he had made at Viñales,⁵ and in the next year he brought out two more papers,⁶ in one of which he figured some

² Alexandre de Humboldt: *Essai Politique l'Ile de Cuba*. Two volumes and map, 364 + 408 pages. Paris, 1826. (See p. 53.)

³ Manuel Fernández de Castro: *Pruebas paleontológicas de que la Isla de Cuba ha estado unida al continente Americano y breve idea de su constitución geológica*. *Anales Acad. Ciencias Habana*, vol. xxi, 1884, pp. 146-165. (See pp. 151, 152.)

⁴ Willard Hayes, T. Wayland Vaughan, and A. C. Spencer: *Report on a geological reconnaissance of Cuba*. 1901.

⁵ Carlos de la Torre: *Excursion Científica a Viñales*. *Anales Acad. Ciencias Habana*, vol. xlv, 1909, pp. 99-103.

⁶ Carlos de la Torre: *Comprobation de l'existence d'un horizon Jurassique dans la région occidentale de Cuba*. *Compte Rendu, Congrès géologique international*, xi, 1910, pp. 1021-1022. Stockholm. Also, 1910: *Investigaciones paleontológicas en las Sierras de Viñales y de Jatibonico*. *Anales Acad. Ciencias Habana*, 1909-10, 33 pages and 21 plates.

unidentified ammonites and noted the occurrence of several Jurassic genera. The existence of Jurassic strata could no longer be doubted, although the exact age of the formations was at that time still unknown. The general results of De la Torre's discoveries were incorporated in the statement prepared by Vaughan for the memoir of the "Stratigraphy of North America," in which reference is made to the occurrence of the genus *Idoceras* [in all probability *Perisphinctes*] in the rocks of the Organ Mountains in Pinar del Rio.⁷

In 1911 Mr. Brown visited Cuba to make collections of Pleistocene vertebrates, and while in Havana received some ammonites from De la Torre. On four subsequent excursions to the island the geology of the western provinces was studied, large collections were obtained—the last being in 1919—numerous cross and columnar sections were made, and the structure and general relations of the formations were worked out. Up to the present time the authors have prepared the following papers on the geology and paleontology of the Jurassic of Cuba. In 1918 the discovery of the Oxfordian beds at Viñales was announced⁸ and, as a part of the results of the paleontological studies, a paper on some of the Cuban *Perisphinctes* was published (1919).⁹ The progress of the geological work done during 1919 and 1920 was incorporated in three papers dealing with the details of correlation,¹⁰ the broad geological features and field relations,¹¹ and some of the upper Oxfordian and lower Lusitanian ammonites of the Viñales region.¹² Further paleontological results have been brought out in a paper on the *Aptychus* shales of the San Vicente section¹³ and one on the Cuban species of *Ochetoceras*, including a general phyletic study of the European and American representatives of that genus.¹⁴

In 1920 Dr. Mario Sanchez Roig published a paper on the Jurassic of Viñales in which he listed and illustrated forty-seven species of

⁷ Bailey Willis: Index to the stratigraphy of North America. Professional Paper No. 71, 1912. (See p. 552.)

⁸ Barnum Brown and Marjorie O'Connell: Discovery of the Oxfordian in western Cuba. Bull. Geol. Soc. Am., vol. 30, 1919, p. 152 (abstract). Presented December, 1918.

⁹ Marjorie O'Connell: Orthogenetic development of the costæ in the *Perisphinctinae*. Am. Jour. Sci., vol. xlviii, 1919, pp. 450-460, 2 figs. Presented before the Paleontological Society of America December, 1918.

¹⁰ Marjorie O'Connell: Further studies on the Jurassic of Cuba. Bull. Geol. Soc. Am., vol. 31, 1920, p. 136 (abstract). Presented December, 1919.

¹¹ Barnum Brown: Cuba. Eleven pages, 57 illustrations, including maps, sections, photographs, 1920. (Privately printed.)

¹² Marjorie O'Connell: The Jurassic ammonite fauna of Cuba. Bull. Am. Mus. Nat. Hist., vol. xlii, 1920, pp. 643-692, plates xxxiv to xxxviii.

¹³ Marjorie O'Connell: New species of ammonite opercula from the Mesozoic rocks of Cuba. American Museum Novitates, No. 28, 1921, 15 pp., 18 text figures.

¹⁴ Marjorie O'Connell: Phylogeny of the ammonite genus *Ochetoceras*. Bull. Am. Mus. Nat. Hist., vol. xlvi, 1922, pp. 387-411.

fossils.¹⁵ The paper is largely a compilation from Burekhardt's monographs. Of the 47 species listed, 27 were not determined specifically, 4 were generically and specifically incorrect, one was generically incorrect, 6 were identified by O'Connell, 6 were not described, and 3 were new but inadequately described. The illustrations, while poor, indicate the richness of the Cuban fauna, but the paper unfortunately is of little scientific value because of its inaccuracy and of the substitution of Burekhardt's descriptions of Mexican species for the descriptions which one would expect to find in a paper on the Cuban fauna.¹⁶

TYPICAL SECTIONS OF THE JURASSIC IN THE PROVINCE OF PINAR DEL RIO

GENERAL STATEMENT

The Province of Pinar del Rio, constituting the western extremity of the island of Cuba, is about 75 kilometers in width, from north to south, and 275 kilometers in length, from northeast to southwest. Physiographically it consists of a northern chain of mountains with a southwest trend, changing to almost due south in the western part. The eastern half of this mountain chain is called the Sierra de Los Organos, or Organ Mountains, and is the region which was particularly studied. The southern flanks of the mountains are overlapped by a series of Tertiary and Recent coastal plain strata dipping gently south to southeast. A section made along a south-north line from any point on the coastal plain, as, for example, Candelaria or San Cristobal, northward into the heart of the mountains, reveals approximately a similar succession of strata. On the plains are Recent or Pleistocene deposits, then follow outcrops of Miocene and Oligocene, the thick limestones of the Cretaceous, and finally the Jurassic beds, which form the main mountain ridges (figure 1.) The Jurassic strata dip southward under the later beds and apparently are continuous under the shallow Gulf of Batabano, for they appear again in the Isle of Pines, 60 miles south of the present southern shoreline of Cuba, from which it is separated by water not more than ten fathoms deep.

In the eastern part of the Province of Pinar del Rio Tertiary rocks are encountered, these being an extension of the plain upon which Havana is built. To the north of Artemisa the Organ Mountains rise

¹⁵ Mario Sanchez Roig: *La Fauna Jurásica de Viñales*. Republica de Cuba, Secretaria de Agricultura, Comercio y Trabajo, Boletín Especial, 1920, 61 pp., 23 plates.

¹⁶ Roig's paper has been reviewed by O'Connell, 1920, *The Jurassic ammonite fauna of Cuba*, loc. cit., p. 644, and will be more fully discussed in the forthcoming memoir on *The Jurassic of Cuba*.

up from beneath the Miocene cover and are composed of Upper Jurassic blue-black, thinly bedded limestones with intercalated shales. In passing westward along the base of the mountains several traverses were made along south-north lines at right angles to the strike. The following are a few typical sections:

CANDELARIA SECTION

A traverse from Candelaria northward for seven miles into the Organ Mountains showed the following succession: At the base is a hard limestone conglomerate about 50 feet thick, made up of limestone and



FIGURE 2.—*Lusitanian and Kimmeridgian black Shales*

The exposure is along the banks of the Rio Hondo, within the Organ Mountain uplift, 6 miles northwest of Candelaria.

gneissic schist boulders and pebbles, the whole resembling a pudding-stone. It usually forms a bed in the three branches of the Rio Hondo and has in large measure determined the fall of these streams. Hard gneissic schists are interbedded in this conglomerate with occasional quartz. These rocks rest on faulted and folded, highly metamorphosed, reddish sandstones, shales, and schists of late Paleozoic or Triassic age. Overlying the conglomerate are about 75 feet of limestones with intercalated shales. These limestones vary from 4 to 6, to 12 inches in thickness, are black, brownish black, weathering blue and, in eroded

sections, are characterized by rounded edges, holes through the blocks, and channeled surfaces frequently traversed by veins of calcite. This part of the series is the most highly fossiliferous, containing ammonites of Kimmeridgian and Portlandian affinities. A loose block, found on one of the mountain sides, but of the same lithic character as these strata, contained a specimen of *Kossmatia victoris* Burckhardt of Portlandian age. Unidentifiable echinoderm plates were also found in these beds, which increase westward to a thickness of about 500 feet in the region of Consolacio, where the lower members contain Kimmeridgian fossils.

The top of the Jurassic section is formed of sheer cliffs of hard gray and gray-black, thin-bedded limestones interbedded with thin seams of brownish shale, which weather white. Some iron is disseminated through the strata and there are occasional lenses of chalcedony. In Morichi Cave, to the east of the Rio Hondo, echinoderm plates were found in these rocks. On a hillside loose, weathered, yellowish-colored blocks were found containing *Haploceras* and what appears to be a small species of *Hamites*. The total thickness of the Jurassic in this region is not over 375 feet and is in marked contrast to the much greater development in the Viñales sections to the west.

SAN CRISTOBAL SECTIONS

Seven miles north of San Cristobal are the headwaters of a small stream, the Rio San Cristobal, parallel to and east of which flows the Rio Hondo. In these stream beds are exposed black shales of Lusitanian and Kimmeridgian age (figure 2). Near the town of Rio Hondo and northward along the banks of the stream of that name the rocks of the uppermost Jurassic are visible. They are the same limestones with intercalated shales which form the outcrops north of Candelaria. The shales, which weather white or fawn-colored, contain aptychi which may be of late Tithonian age, but which more closely resemble Lower Cretaceous species.¹⁷ They are found in outcrops northeast of Mount Pimiento, an igneous peak lying to the west of the Rio Hondo, and also on the Finca of Rafael Begoa, 9 miles north of San Cristobal. At Morichi and at Paradon Sariego, northwest of Mount Pimiento, these strata present vertical cliffs nearly 200 feet in height with the bedding planes in their original condition. The summit of the high mountain north of San Cristobal, known as Peña Blanca, is completely covered by these white limestones. Within the range of the mountains they appear as bold,

¹⁷ Marjorie O'Connell: New species of ammonite opereula from the Mesozoic rocks of Cuba. American Museum Novitates, No. 28, 1921, 15 pp., 18 text figures.

sheer, white faces and often stand out as gigantic monuments. At Finca Rosario, seven miles north of San Cristobal and to the west of the stream of that name, the Kimmeridgian and Portlandian occur.

SECTIONS NEAR SAN DIEGO DE LOS BAÑOS

Thirty kilometers southwest of San Cristobal lies the town of San Diego de los Baños, through which the river of that name flows. Along the banks the Oxfordian shales are exposed with the Cretaceous beds overlying them nonconformably (figure 3). Four kilometers west of



FIGURE 3.—*Section of west Side of River San Diego de los Baños*

The view is opposite the sulphur baths. Steeply dipping Oxfordian shales cut through by diorite intrusion.

San Diego de los Baños, at the loma of La Güira, is a thick exposure of the Jurassic shales ranging from the Oxfordian through the Lusitanian and possibly into the lower Kimmeridgian (figure 4).

VINALES SECTION

Along the wagon road going north from the city of Pinar del Rio there are exposed the Tertiaries, the Cretaceous, and finally the Jurassic, which comes to view in the Viñales basin (figure 5). The best sections for the Oxfordian are seen near the Bodega La Guasasa, between Viñales



FIGURE 4.—*Oxfordian and Lusitanian black Shales with Ammonite accretions*.
The photograph was taken at La Güira, 4 kilometers west of San Diego de los Baños.



FIGURE 5.—*Organ Mountains*

Showing ocean sculpturing. Old schistose shales at base overlain unconformably by the Jurassic limestones. Viñales at the right, beyond the hill in the foreground. View toward northeast.

and Vicente, in the mountain pass known as La Puerta del Ancón (figure 6). The black limestones and shales are covered by a stalactitic drip which seals the bedding planes and preserves the rocks from erosion (figure 7). It was here that De la Torre made his first collections, and the locality has since proved to be one of the richest for ammonites. The fossils occur in great numbers in the concretions which are found in the talus at the bottom of the cliffs. About 12 kilometers northeast of Viñales, at San Vicente (figure 8), the limestones are of Kimmeridgian age and contain several new species of ammonites. Along the road



FIGURE 6.—*Puerta Ancón, looking North*
Stalactitic drip is shown on the face of the cliff.

the limestones can be seen dipping north on the northern side of the Organ Mountain uplift (figure 9). Six miles northeast of Viñales is one of the massive limestone magotes with the pre-Oxfordian shales and schists forming the lower hills to the north (figure 10). At the foot of this mountain and in many outcrops near the copper mine Constancia the black limestone accretions are abundant (figure 11) and they contain ammonites, pelecypods, gastropods, fishes, and marine reptiles. One small gastropod, *Cerithium cubanensis*, new species, found at Constancia, also occurs at San Vicente and at Finca Rosario, northwest of San Cristobal. The age of these strata ranges from Oxfordian through lower

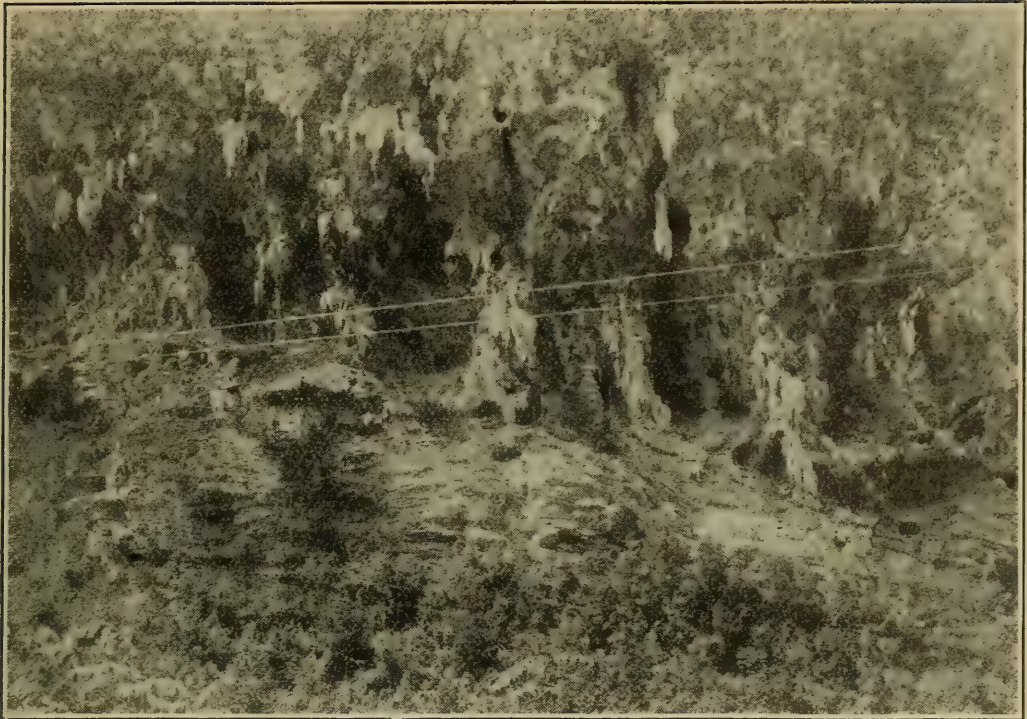


FIGURE 7.—*Details of Cliff shown in Figure 6*

The Oxfordian limestones are preserved from erosion by the stalactitic drip which seals the bedding planes.



FIGURE 8.—*View looking North toward Esperanza from center of Mountain Valley near San Vicente*

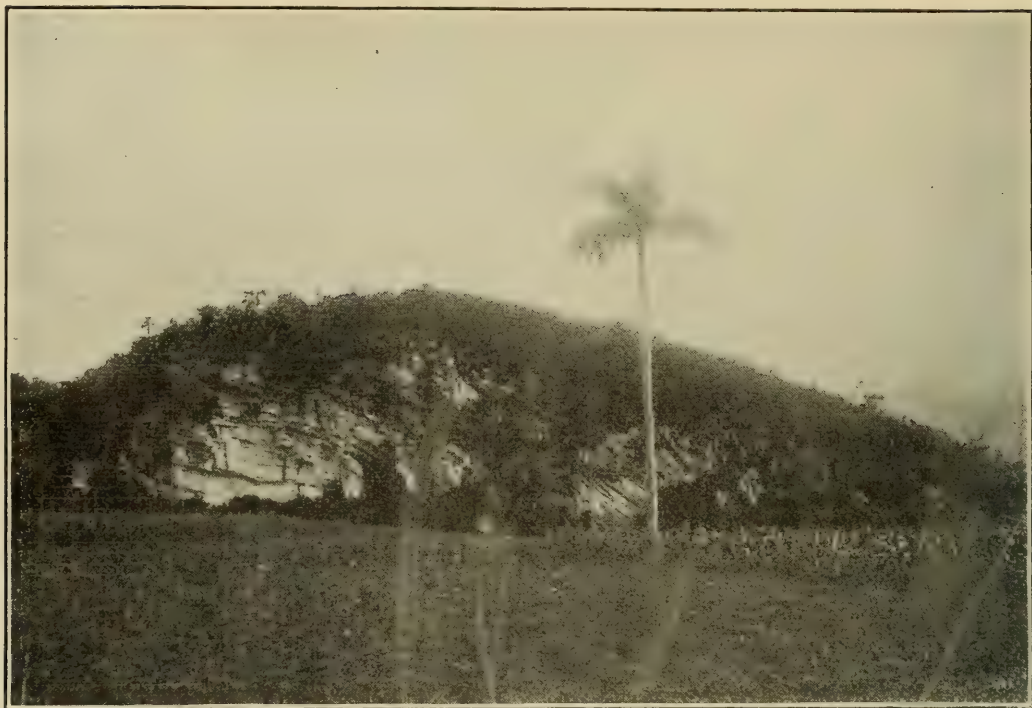


FIGURE 9.—*A Limestone Magote*

This hill is on the left side of road, north of Viñales, and on north axis of mountain uplift; beds dipping north.



FIGURE 10.—*A Limestone Magote*

This photograph was taken from hill north of copper mine, Constancia, 6 miles north-east of Viñales. Ammonites abundant in accretions at foot of mountain. Pre-Middle Jurassic schistose shales form the low rolling hills beyond at right.

Kimmeridgian, the total thickness being over a thousand feet. The pronounced folding of the underlying schists on which the Oxfordian limestones rest unconformably is well shown on the road to Esperanza, north of the limestone mountains (figure 12).

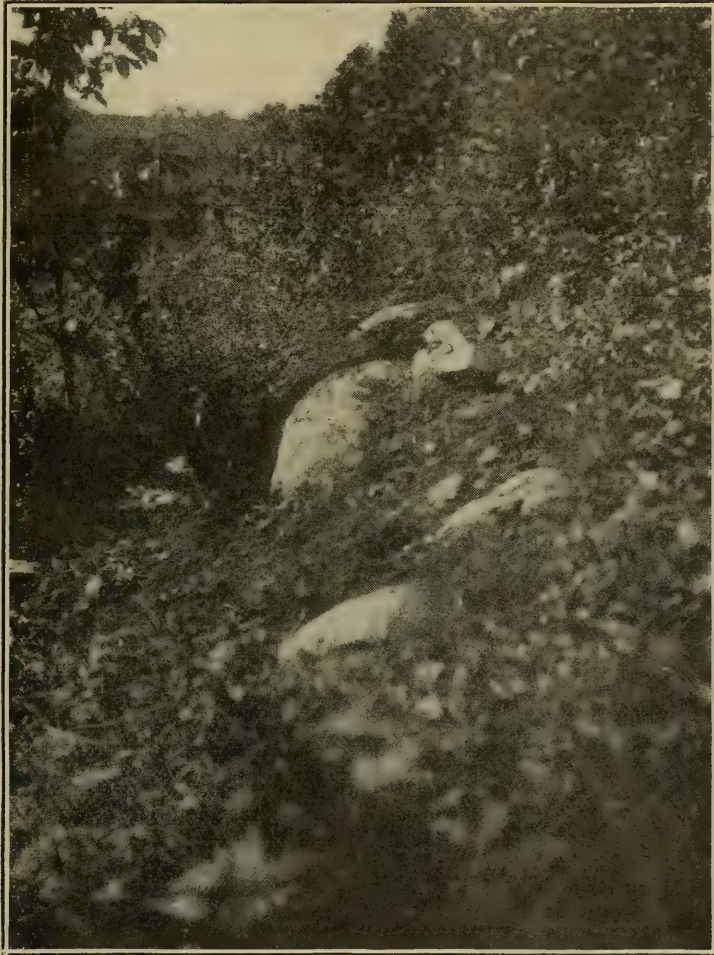


FIGURE 11.—Accretions filled with *Ammonites*, *Fishes*, and *Marine Reptiles*

The photograph was taken near Mina Constanca.

GENERAL SUMMARY OF FIELD RELATIONS AND THEIR SIGNIFICANCE

The Jurassic strata of Pinar del Rio, first seen in the eastern foothills of the Organ Mountains, north of Artemisa, are less than 400 feet thick north of Candelaria, but westward increase in thickness to over a thousand feet, in the Viñales section. Concomitantly with this change in thickness there is an increase in the age of the strata, lower members of the series outcropping westward. Thus, in the east the Kimmeridgian and Portlandian rest with a basal conglomerate on the old metamorphosed schists, but westward the Lusitanian and Oxfordian, and perhaps

even older, beds come in, while each formation thickens westward. The stratigraphic relation is clearly that of a marine transgressive overlap toward the east, the late Middle Jurassic sea having encroached upon the western end of the Cuban landmass, which continued to sink through late Jurassic time. The individual divisions of the rock series are thickest in the Viñales region, and thin out eastward, while the basal conglomerate occupies a diagonal position and becomes progressively younger toward the east, as indicated in the restored cross-section (figure 13). Above the Jurassic rocks are about 1,000 feet of irregular, discontinuous limestones with thick beds of dark-colored shale in the upper measures



FIGURE 12.—*Folded Schists North of the Limestone Mountains on the Road to Esperanza*

and lighter-colored marly shales with sandstone strata near the base. Numerous *Rudistes* attest the Cretaceous age of these beds, which also contain gastropods, *Ostrea* and other pelecypods. Submergence must, therefore, have continued through Cretaceous time, although there may have been a retreat of the sea at the end of Jurassic or in Eo-Cretaceous time.

At the end of Cretaceous time folding and tilting took place, the vertical uplift being greater in the western part of the Province of Pinar del Rio than in the eastern. These diastrophic changes probably continued throughout the Paleocene and were synchronous with similar movements in many other parts of the world at that time. During that

long period of uplift and erosion a great part of the Cretaceous cover was stripped off from the elevated central areas. When the island was in whole or in part submerged by the Oligocene sea, sediments were deposited in many places directly upon the eroded Jurassic rocks, as the unconformable contacts indicate. On account of the differential uplift of the western end of the Organ Mountains, the Upper Jurassic rocks have there been worn away, so that only the lower part of the section is preserved, while eastward the stratigraphically higher, but topographically lower, beds are shown (figure 14). But for this differential uplift the Jurassic section would be complete in the latitude of Viñales; and, since strata ranging from the Oxfordian into the Kimmeridgian have been found at Constancia, it is possible that there may even be isolated outcrops of the Portlandian remaining. That such outcrops probably occur is indicated by the presence of the Portlandian species *Simbirskites mexicanus* Burckhardt and *Kossmatia zacatecana* Burckhardt in concretions which, according to Dr. Roig's statement, came from sections north of Viñales.

CORRELATION OF THE JURASSIC OF CUBA AND MEXICO

The Jurassic ammonite fauna of Cuba bears a close resemblance to that of Mexico, there being a sufficient number of species in common to make possible a general correlation. Burckhardt, in his two monographs on the Jurassic of Mexico,¹⁸ has made known to us the stratigraphic and faunal succession in San Pedro del Gallo, in the State of Durango, and in Mazapil. In the former region there are some 1,700 meters of black shales and limestones ranging from Lower or Middle Jurassic age through the Portlandian and succeeded by Cretaceous strata. The ammonites are found in black, bituminous concretions identical in color and lithological character with those in Cuba. Two hundred and fifty kilometers east of San Pedro del Gallo is the very thin section at Mazapil, where there are less than 100 meters of shales and limestones representing the Kimmeridgian and Portlandian and resting upon a thick series of limestones and marls containing pelecypods, corals, and Nerineas of uncertain age. Faunally, the Cuban Jurassic is more like that of San Pedro del Gallo than that of Mazapil. Both regions contain a certain number of widespread European species which make intercontinental correlations possible, but they also show many provincial forms which have no very near relatives in the European fauna, but which are

¹⁸ Carl Burckhardt: La Faune Jurassique de Mazapil. Inst. Geol. Mexico, Boletin No. 23, 1906, 216 pp., 43 plates, and Faunes Jurassiques et Cretaciques de San Pedro del Gallo. Inst. Geol. Mex., Boletin No. 29, 1912, 264 pp. and 46 plates.

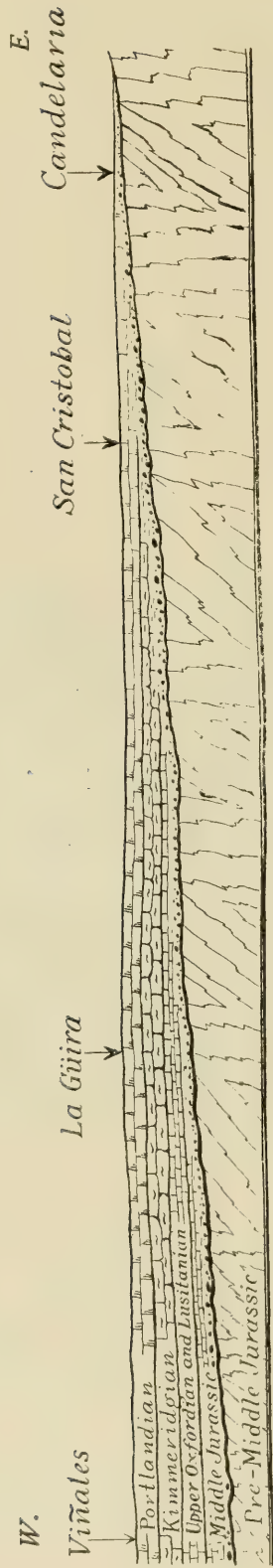


FIGURE 13.—Ideal Cross-section showing the Marine progressive Overlap of the successive Middle and Upper Jurassic Formations from Viñales to Candelaria

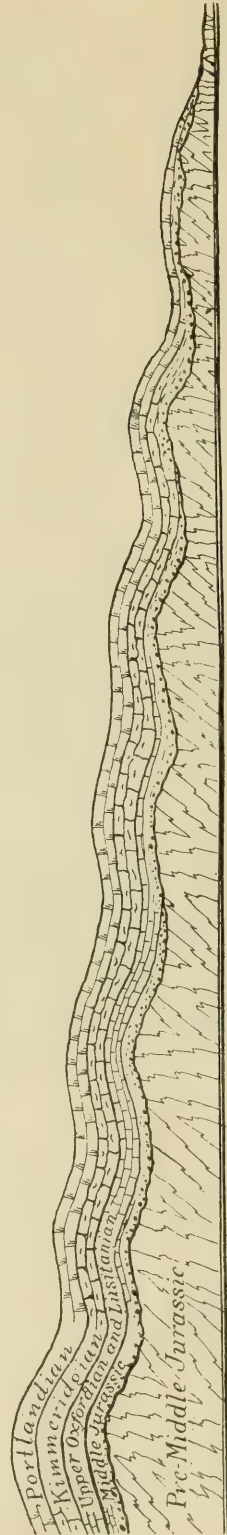


FIGURE 14.—Ideal Cross-section showing the early Tertiary Folding and Elevation of the Strata represented in Figure 13
The uplift was greater in the west than the east. The overlying Cretaceous strata are not indicated.

EUR				CUBA
England		France		Pinar del Rio
Upper, or Portland, Oolites	Portlandian Purbeckian	Portlandien	Supérieur (Purberckien)	 <i>Simbirskites mexicanus</i> , <i>Kossmatia zacatecana</i> , <i>K. victoris</i>
			Inférieur	
	Kimmeridgian	Kimmeridgien	Virgulien Ptérocérien	<i>Haploceras</i> aff. <i>flalar</i> , <i>Ataxioceras lothari</i> , <i>Perisphinctes ribeiroi</i> , <i>P. cf. plebejus</i> , new species of <i>Ataxioceras</i> , <i>Oppelia</i> and <i>Perisphinctes</i>
	Corallian	Lusitanien	Séquanien (Astartien) Rauracien Argovien	<i>Ataxioceras virgulatum</i> , <i>Ochetoceras marantianum</i> , <i>O. semifalcatum</i> , <i>Perisphinctes</i> many species, <i>Haploceras</i> <i>Ochetoceras canaliculatum burckhardti</i> , <i>O. mexicanum</i>
Middle, or Oxford, Oolites	Oxfordian	Oxford Clay	Oxfordien	<i>Aspidoceras perarmatum</i> , <i>Perisphinctes plicatiloides</i> , <i>Perisphinctes durangensis</i>
		Callovian	Callovien	New species of <i>Perisphinctes</i> and a new nautiloid showing affinities with Callovian species of Europe
Lower Oolites	Bathonian	Bathonien		New species of <i>Perisphinctes</i> showing affinities with late Bajocian and Bathonian species of Europe
	Bajocian	Bajocien		New species of <i>Strenoceras</i> related to <i>S. niortense</i>

to be regarded as species evolved under the rather restricted environmental conditions obtaining in a small embayment of the Atlantic. Side by side with the European elements in the American fauna lived the species which may be regarded as peculiar to the western hemisphere, although evidently derived from European forms. Thus the Oxfordian fauna of Mexico and Cuba contains *Perisphinctes plicatiloides* O'Connell¹⁹ a species related to, yet specifically distinct from, the widespread *P. plicatilis* Sowerby and D'Orbigny of Europe and Asia. In the Lusitanian and Kimmeridgian there are American species of *Ochetoceras* corresponding to, but not identical with, European species.²⁰ The Portlandian fauna of Cuba and Mexico contains the typical European genera *Simbirskites* and *Kossmatia*, represented, however, by American species (see correlation table).

The major part of the large Oxfordian fauna of Durango, consisting of twenty species of ammonites described by Burekhardt, comes from the grayish concretions and limestone beds which are intercalated in the lower series of rocks. There is a gradual lithologic change upward in the series, marked by the frequent occurrence of black shales and the appearance of black limestone nodules, which become more numerous as the top of the Oxfordian is reached. There is a complete lithologic transition into the overlying Kimmeridgian (*sensu lato*) beds, in which the concretions are very numerous, consisting of hard, compact, homogeneous black limestone and containing Aucellas and many species of *Idoceras*. The rocks of this age vary from a few meters up to 400 meters in thickness in the environs of San Pedro, but to the southeast, at Mazapil, they are only from 15 to 30 meters thick, although of about the same lithic character, with the fossils occurring as impressions in the argillaceous shales and entire in the black limestone nodules.

The occurrence of these black, bituminous concretions is, therefore, no indication of the age of the rocks in which they occur; indeed, they are found at successive horizons throughout the entire Jurassic series at Durango, from the higher beds of the upper Oxfordian through the Portlandian—that is, through a thickness of over a thousand meters—and even on upward into the Cretaceous. In Cuba such concretions are found even lower in the Oxfordian and through all the succeeding divisions of the Jurassic, so that we must conclude that there is no stratigraphic value in the concretions over either a limited or a wide area,

¹⁹ Marjorie O'Connell: The Jurassic ammonite fauna of Cuba. Bull. Am. Mus. Nat. Hist., vol. xlii, 1920, pp. 643-692 (p. 670, pl. xxxvi, figs. 1 and 2).

²⁰ Marjorie O'Connell: The phylogeny of the ammonite genus *Ochetoceras*. Bull. Am. Mus. Nat. Hist., vol. xlii, 1922, pp. 387-411.

Correlation Table for the Middle and Upper Jurassic Formations of Europe, Mexico, and Western Cuba

EUROPE					MEXICO		CUBA	
England		France		Paleontological zones	Alps	San Pedro del Gallo	Mazapil	Pinar del Rio
Upper, or Portland, Oolites	Portlandian	Portlandien	Supérieur (Purberckien)	<i>Berriasella callisto</i> <i>Perisphinctes contiguus</i>	Tithonian	<i>Berriasella behrendseni</i> <i>Simbirskites mexicanus</i> , <i>Kossmatia</i> , <i>Hoplites</i> , <i>Durangites</i> <i>Holcostephanus</i> aff. <i>pronus</i>	<i>Berriasella callisto</i> <i>Kossmatia zacatecana</i> , <i>K. victoris</i> <i>Perisphinctes</i> intermediate between <i>contiguus</i> and <i>transitorius</i> <i>Aspidoceras cyclotum</i> , <i>Virgatites mexicanus</i>	<i>Simbirskites mexicanus</i> , <i>Kossmatia zacatecana</i> , <i>K. victoris</i>
	Kimmeridgian		Kimmeridgien	Inférieur		<i>Oppelia lithographica</i> and <i>Pachyceras portlandicus</i>	Hiatus	
Middle, or Oxford, Oolites	Corallian	Lusitanien	Virgullien	<i>Aulacostephanus pseudomutabilis</i>	Acanthicus beds	Unknown at San Pedro	Shales with <i>Waagenia</i> and <i>Aspidoceras avellanoides</i>	<i>Haploceras</i> aff. <i>fialar</i> , <i>Atarioceras lothari</i> , <i>Perisphinctes ribeiroi</i> , <i>P. cf. plebejus</i> , new species of <i>Atarioceras</i> , <i>Oppelia</i> and <i>Perisphinctes</i>
			Ptérocérien	<i>Streblites tenuilobatus</i>		<i>Haploceras</i> cf. <i>fialar</i> , <i>Streblites</i> , <i>Nebroditis</i> , <i>Idoceras</i> , many species, <i>Aucella</i> of <i>A. pallasii</i> group	Beds with <i>Haploceras fialar</i> <i>Aucella</i> band <i>Idoceras</i> beds	
			Séquanien (Aspartien)	<i>Perisphinctes achilles</i>		Bicristatum beds	<i>Atarioceras virgulatum</i> <i>Ochetoceras canaliculatum burckhardtii</i> , <i>O. mexicanum</i>	Limestones with nerineas and corals; pelecypods and corals in shales. Exact age undeterminable	Atarioceras virgulatum, Ochetoceras marantianum, O. semisulcatum, Perisphinctes many species, Haploceras Ochetoceras canaliculatum burckhardtii, O. mexicanum
	Rauracien	<i>Peltoceras bicristatum</i>	Transversarium beds	<i>Perisphinctes durangensis</i> , <i>P. elizabethaeformis</i> , <i>P. plicatiloides</i>	<i>Aspidoceras perarmatum</i> , <i>Perisphinctes plicatiloides</i> , <i>Perisphinctes durangensis</i>			
Oxfordian	Oxford Clay	Argovien				<i>Peltoceras transversarium</i>	Limestone of Vils			New species of Perisphinctes and a new nautiloid showing affinities with Callovian species of Europe
		Oxfordien	<i>Cardioceras cordatum</i> and <i>Aspidoceras perarmatum</i> <i>Quenstedticeras mariae</i> and <i>Q. præcordatum</i> <i>Quenstedticeras lamberti</i>	Klaus beds	New species of <i>Perisphinctes</i> ; showing affinities with late Bajocian and Bathonian species of Europe			
	Callovian	Callovien	<i>Rcineckia anceps</i> <i>Macrocephalus macrocephalites</i>			Garda beds					New species of Strenoceras related to S. niortense
Lower Oolites	Bathonian	Bathonien	<i>Oppelia aspidoides</i> <i>Oppelia fusca</i>					
	Bajocian	Bajocien	<i>Strenoceras garantianum</i> <i>Witchellia romani</i> <i>Emileia sauzei</i> <i>Witchellia leviuscula</i>					

despite the fact that it has been appealed to in the correlation of the Cuban and Mexican faunas.

The Oxfordian ammonite fauna described by Burckhardt from Durango contains, as we have seen, twenty species, ten of which are identical with or to be compared with European forms, while the other ten are new, but are derivatives from European species. The fauna as a whole belongs unquestionably to the zones of *Peltoceras bimammatum* (= *bicristatum*) and *P. transversarium*, since it contains elements of both.

Turning to Cuba, we find that the rocks are of similar lithic character, but that the entire series is thinner than it is in Durango. Approximately the same paleontological succession is observed, but a larger number of zones can be recognized and the series includes older divisions of the Jurassic than have yet been found in Mexico. The chief species in common between Cuba and Mexico are: *Perisphinctes plicatiloides* O'Connell, *P. durangensis* Burckhardt in the upper Oxfordian; *Ochetoceras canaliculatum* var. *burckhardti* O'Connell and *O. mexicanum* Burckhardt in the lower Lusitanian zone of *Peltoceras transversarium*; *Ataxioceras virgulatum* (Quenstedt) in the middle Lusitanian zone of *Peltoceras bicristatum*; *Haploceras* aff. *fialar* (Oppel) in the lower Kimmeridgian zone of *Streblites tenuilobatus*; *Simbirskites mexicanus* Burckhardt, *Kossmatia victoris* Burckhardt, and *K. zacatecana* Burckhardt in the upper Portlandian.

It is impossible to distinguish as a separate unit in Mexico and Cuba the zone of *Perisphinctes achilles*, which is found to constitute the upper Lusitanian in the French and Argovian Jura. The upper Kimmeridgian zone of *Aulacostephanus pseudomutabilis* does not appear to be present either in Cuba or Durango, but it may be represented at Mazapil by the *Waagenia* beds. During early Portlandian (Portlandian *sensu stricto*) time there was emergence and erosion in Mexico and probably also in Cuba, for only upper Portlandian strata (Purbeckian) have been found in the two countries.

CORRELATION OF THE JURASSIC OF CUBA AND EUROPE

CLASSIFICATION OF MIDDLE AND UPPER JURASSIC OF WESTERN CUBA AND SOUTHERN EUROPE

When the ammonite fauna of Cuba is compared with that of Europe, there is found to be a sufficiently close resemblance to indicate that both belong to the same geographical province—the Atlantic. A small number of cosmopolitan European species also occur in Cuba, while nearly

of formation names, for not only does the usage vary from country to country, but also within each country. It would be out of place in this paper to discuss the reasons for adopting one set of terms rather than another, in the European classification, but it may be stated that, in so far as possible, we have employed the formation names of the type sections of England, whence all of the names were derived, and have used the detailed paleontological zones now recognized on the Continent, where the marine series is more completely developed than in Great Britain. In England the Middle or Oxford Oolites include the Oxfordian below and Corallian above, the former being again divided into the Callovian or Kellaways rock, containing *Kepplerites calloviense*, a species found in the zone of *Macrocephalites macrocephalus* on the Continent, and the Oxford clay with *Cosmoceras jason*, *C. ornatum*, *Quenstedticeras lamberti*, *Peltoceras athleta*, and *Cardioceras cordatum*. These two divisions in their faunal content correspond to the upper part of Quenstedt's Brown Jura ζ . The Corallian, the upper part of the Oxford Oolites, shows at the base the zone of *Aspidoceras perarmatum* and, higher up, the zone of *Perisphinctes plicatilis*, the two being the equivalents of Quenstedt's White Jura α and β , respectively, corresponding to Oppel's zones of *Transversarius* and *Bimammatus*.²³

De Lapparent²⁴ uses Callovien in a somewhat broader sense than the English do, making it include the Kellaways rock and the lower Oxford clay, with *Quenstedticeras lamberti* and *Cosmoceras jason* as the zonal fossils. His Oxfordien contains a lower division corresponding to the English lower Calcareous grit, and an upper division which he calls the Argovien and which is about the equivalent of the lower part of the English Corallian. Coordinate with the Oxfordien is the next younger division, the Séquanien, divided into the lower, or Rauracien,²⁵ with *Peltoceras bicristatum*, and the upper, or Astartien, division, the Séquanien (*sensu stricto*), with *Ostrea deltoidea*. As De Lapparent uses these substages, they bridge the paleontological zones and are therefore difficult to employ in correlation. Thus the Rauracien contains the zone of *Peltoceras bicristatum* and a part of the zone of *Perisphinctes achilles*, while the Séquanien (*sensu stricto*) is considered to embrace the beds in which *P. achilles* is dominant and also the lower *Tenuilobatus* beds of the Swiss region. The Kiméridgien has been divided by Lappa-

²³ *Ammonites bimammatus*, which is the zonal fossil, is now designated *Peltoceras bicristatum* (Kilian, Bull. Soc. Geol. France (4), ii, p. 783), but the name *Bimammatus* zone is firmly fixed in the literature, having been employed for sixty years, and it is still widely used instead of *Bicristatum* zone.

²⁴ A. de Lapparent: *Traité de Géologie*. Paris, ii, 1906, p. 1245.

²⁵ Proposed by Greppin, 1867.

rent into the Ptérocérien, the equivalent of the English lower Kimmeridgian clay, and the Virgulien,²⁶ marking the horizon of *Aulacostephanus pseudomutabilis* and *A. eudoxus* (see table, page 655). In Germany it is not uncommon for writers to divide the Upper Jurassic into three stages—the Oxfordian, Kimmeridgian, and Portlandian—using Oxfordian in a broad sense equivalent to the English Oxford Oolites.

In 1893 Choffat²⁷ introduced the formation name Lusitanian for the lower Malm of Portugal. The series of formations exposed in the region around Torres Vedras, north of Lisbon, rests upon strata of Callovian age and is succeeded by Kimmeridgian beds corresponding to the Ptérocérien of France. The Lusitanian beds contain fossils characteristic of the zones of *Peltoceras transversarium* and *P. bicristatum* and a few which, elsewhere in Europe, range into the zone of *Streblites tenuilobatus*. They thus correspond essentially to the Argovien, Rauracien, and Séquanien stages on the Continent and to the Corallian of England. Therefore the geographical name Lusitanian may appropriately be used to replace the lithological name Corallian, as Haug²⁸ has suggested. The Purbeckian should be regarded as a substage of the Portlandian (*sensu lato*), since it is only a fresh-water phase of the latter which, on the Continent, is represented by a complete marine series.

If we incorporate these changes and substitutions, we arrive at the following subdivisions for the marine Middle and Upper Jurassic of western and south central Europe:

Upper Jurassic.	{	Portlandian. Kimmeridgian. Lusitanian.
Middle Jurassic.	{	Oxfordian. Callovian. Bathonian. Bajocian.

This is the subdivision adopted by Haug (1908-11) and appears to be the one most strictly in accord with the historical development of the naming of the formations in England. Furthermore, it does away with the objectionable lithological names, Oxford clay and Coral Rag, or Corallian.

²⁶ Proposed by Thurmann.

²⁷ Paul Choffat: Description de la Fauna Jurassique du Portugal. Classe des Céphalopodes. Première série: Ammonites du Lusitanien de la Contrée de Torres-Vedras. Lisbonne, 1893, 82 pp., 20 plates. (See p. 1.)

²⁸ E. Haug: Traité de Géologie, 1908-11, p. 1045.

The faunal zones, while named for successive species of ammonites, are based upon the character of the entire faunal assemblage at each horizon. Certain species are found in two or more zones and are therefore not quite so valuable for correlation purposes as are those which have been selected as the zone fossils because of their more limited range. The Upper Jurassic paleontological zones are those which have been recognized in the Argovian, Swabian, and Franconian Jura, the Alpine geosyncline, France and Portugal. Many of the species of these zones range throughout the Mediterranean province from southern France, through the Alps and down into northern Italy, in the Balkans, Asia Minor, and northern Africa.

COMPARISON OF CUBAN SUCCESSION WITH EUROPEAN STANDARD

So far, there has been found in the Cuban fauna only one of the European zonal fossils, namely, *Aspidoceras perarmatum* (Sowerby), but, many of the species which are commonly associated with the zone fossils in Europe do occur in Cuba, so that it has been possible to recognize the presence of the upper Oxfordian, the two lower zones of the Lusitanian, the lower Kimmeridgian, and the upper Portlandian. There are a number of new species showing affinities with Bajocian, Bathonian, and Callovian forms; but, since none of the previously known European species of any of those stages has yet been discovered, we hesitate to say positively that those divisions of the Jurassic are represented in Cuba, although there is considerable evidence that they are.

The Lusitanian and Kimmeridgian species are either identical with or nearly allied to species in the Jurassic rocks of Swabia, Württemberg, and cantons Aargau and Baden in Switzerland. The zone of *Peltoceras transversarium*, recognized at Viñales, Constancia, and La Güira, contains *Ochetoceras canaliculatum* var. *burckhardti* O'Connell, which also occurs in Mexico and is a geographical variant of the widespread *O. canaliculatum* (Buch) which characterizes this zone in England, France, Spain, Portugal, southern Germany, Persia, and northern Africa. Another European species characteristic of this zone is *Perisphinctes mindove* Siemiradzki, which occurs at Constancia, north of Viñales. It was first described from Poland and has since been found in France and Portugal. Finally, there are several new species belonging to the genera *Ataxioceras*, *Grossouvria*, and *Perisphinctes*.

The zone of *Peltoceras bicristatum*, recognized at Viñales and Constancia, is indicated by the occurrence of *Ataxioceras virgatum* (Quenstedt), *Ochetoceras marantianum* (D'Orbigny), *O. semifalcatum*

(Oppel), and new species of *Ataxioceras* and *Perisphinctes* and *Haploceras* species.

The most complete faunal representation is that for the zone of *Streblites tenuilobatus*, which occurs at Constancia, San Vicente, La Güira, and Finca Rosario. It contains new species of *Perisphinctes*, *Oppelia*, *Ataxioceras*, *Cerithium* and the following European representatives:

Ataxioceras lothari (Oppel).
Perisphinctes ribeiroi Choffat.
P. cf. plebejus Neumayr.
Haploceras aff. *flalar* (Oppel).

There is no indication, so far, of the existence of the lower Portlandian (*sensu lato*) in Cuba, but three upper Portlandian species have been identified, namely:

Simbirskites mexicanus Burckhardt.
Kossmatia zacatecana Burckhardt.
Kossmatia victoris Burckhardt.

The first two were found near Viñales, according to Roig, while the third was found north of Candelaria, indicating that the Portlandian occurs in the eastern and western parts of the section.

The exact stratigraphic position of the *Aptychus* shales has not yet been determined, but the fossils themselves seem to indicate a late Tithonian or early Cretaceous age. The following species have been described from the region north of San Cristobal:²⁹

Aptychus cristobalensis O'Connell.
Aptychus cubanensis O'Connell.
Aptychus pimientensis O'Connell.

The majority of the new species which have been described³⁰ belong to the Lusitanian and lower Kimmeridgian. The Lusitanian species show affinities with species found in the zones of *Peltoceras transversarium* and *bicristatum* of Portugal and France, while the Kimmeridgian species find their nearest relatives in the zone of *Streblites tenuilobatus* of Baden, Oberbuchsitten, and Solothurn in Switzerland.

It was not until late Portlandian time that genera of north European origin invaded the Atlantic waters and reached Cuba and Mexico. Since *Simbirskites* and *Kossmatia* have long been regarded as particularly characteristic of the boreal sea which covered Russia, their occurrence at much

²⁹ Marjorie O'Connell: New species of ammonite opercula from the Mesozoic rocks of Cuba. *Am. Mus. Novitates*, No. 28, 1921, 15 pp., 18 figs.

³⁰ Manuscript not yet published.

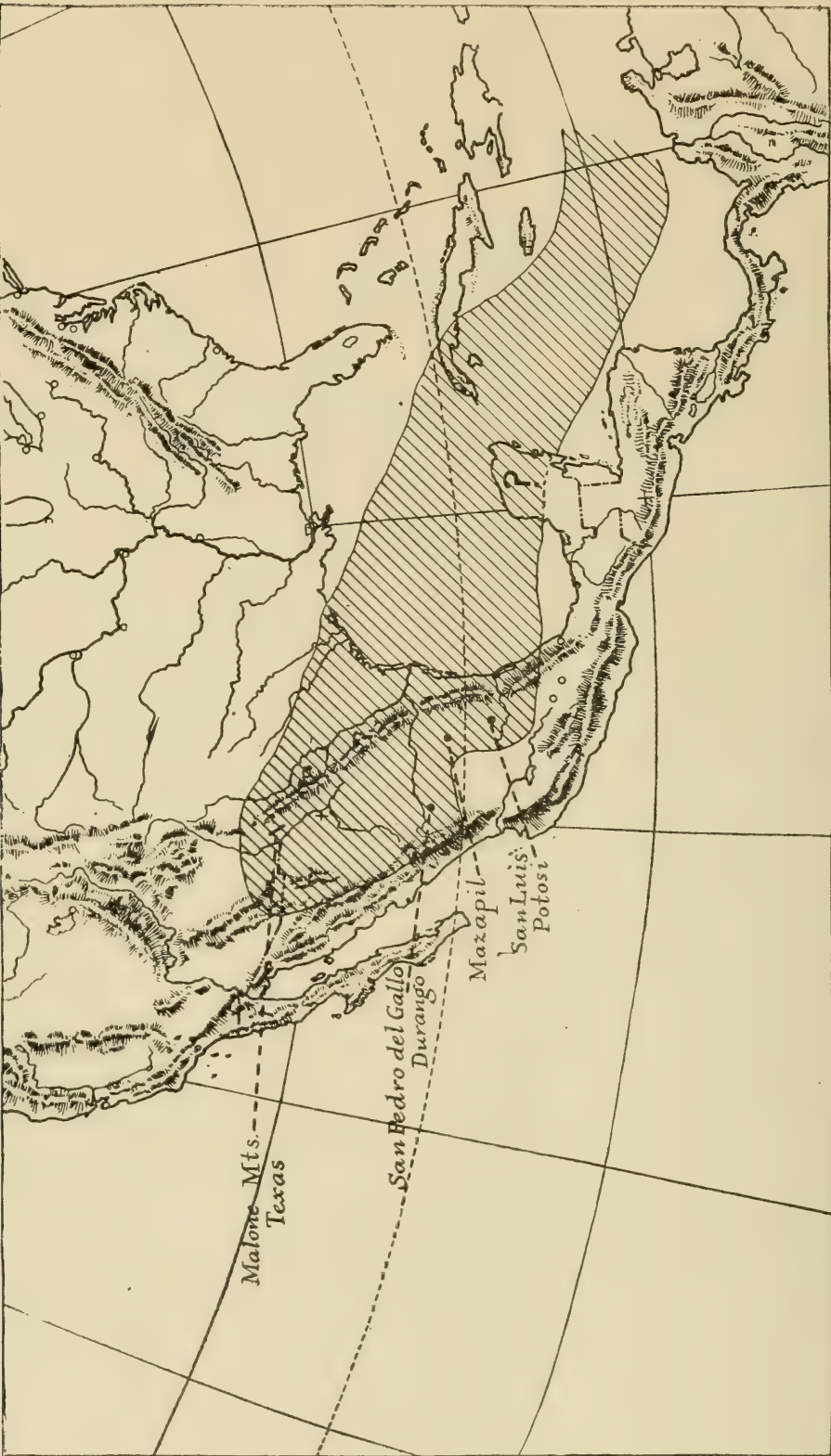


FIGURE 15.—Paleogeographic Map showing the maximum Transgression of the Sea during Portlandian Time

The outline base map, of which this illustration is a reproduction, was prepared by J. Paul Goode for class use and is presented here through the courtesy of the University of Chicago Press, Chicago, Illinois. The paleogeographic map is new and was prepared by the authors.

lower latitudes is interesting and suggests an amelioration of climate at the end of the Jurassic and the merging of the climatic zones which were more marked earlier in that period.

The maximum transgression of the West Indian Jurassic embayment of the Atlantic evidently obtained during the Portlandian, for fossils of that age are found in the easternmost Jurassic outcrops in Cuba, in the Malone Mountains in Texas,³¹ and in Mazapil and Durango in Mexico (figure 15.)

SUMMARY

The Organ Mountains, in the Province of Pinar del Rio, western Cuba, are composed for the most part of black limestones and shales, weathering brown or white and characterized by layers of fossiliferous concretions (of the accretion type) containing ammonites, pelecypods, gastropods, and, in some localities, fishes and marine reptiles. The formations are thin at the eastern end of the mountains, in the regions north of Candelaria and San Cristobal, where they are about 375 feet thick, but increase westward, attaining their maximum development of upward of a thousand feet in the section between Viñales and Constancia. The westernmost outcrops are seen at Guane. The strata dip down under the Tertiaries, which form the coastal plain bordering the mountains, and reappear in the Isle of Pines to the south.

The formations range from the Middle through the Upper Jurassic, the existence of the Bajocian, Bathonian, and Callovian at Constancia and La Güira being somewhat doubtful, because all of the ammonites upon which those older horizons were determined are new species. The presence of rocks of upper Oxfordian, Lusitanian, Kimmeridgian, and upper Portlandian age is indicated by the occurrence of species of ammonites characteristic of those formations in Europe and also of many species which are new but are related to European Neo-Jurassic forms. In the eastern foothills of the Organ Mountains the upper Portlandian is found resting with a basal conglomerate on ancient folded rocks; westward the Kimmeridgian, Lusitanian, Oxfordian, and older Jurassic strata come in successively beneath the Portlandian, the relation being clearly indicative of a marine transgression from west to east, the basal conglomerate becoming younger in age eastward. The eastern shore-line of the embayment of the Jurassic Atlantic, at the period of maxi-

³¹ F. W. Cragin: Paleontology of the Malone Jurassic formation of Texas, with stratigraphic notes on Malone Mountain and the surrounding region near Sierra Blanca, Texas, by T. W. Stanton. U. S. Geol. Survey Bull. 266, 1905, 109 pp., pls. ii-xxix.

mum transgression in late Portlandian time, passed through the eastern end of the Province of Pinar del Rio. No Jurassic strata have been found farther east, and we may feel certain that they were not deposited, since Cretaceous beds rest directly upon the old folded schists.

The submergence which had already been in progress throughout Meso- and Neo-Jurassic time continued during the Cretaceous. At the end of the Mesozoic the sea retreated, and there ensued a long period of elevation, folding, and erosion lasting through Paleocene and most of Eocene time. During the remainder of the Tertiary era Cuba was more or less covered by the sea, the submergence being greater over the eastern than the western end.

THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS, 1922

President:

CHARLES SCHUCHERT, New Haven, Conn.

Vice-Presidents:

HENRY S. WASHINGTON, Washington, D. C.

ROBERT T. HILL, Glendale, Calif.

W. D. MATTHEW, New York City

T. L. WALKER, Toronto, Canada

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History,
New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1922)

T. W. VAUGHAN, Washington, D. C.

GEORGE F. KAY, Iowa City, Iowa

(Term expires 1923)

L. C. GRATON, Cambridge, Mass.

G. D. LOUDERBACK, Berkeley, Calif.

(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio

BULLETIN

OF THE

Geological Society of America

VOLUME 33 NUMBER 4
DECEMBER, 1922



JOSEPH STANLEY-BROWN, EDITOR

PUBLISHED BY THE SOCIETY
MARCH, JUNE, SEPTEMBER, AND DECEMBER

CONTENTS

	Pages
Devonian of Oklahoma, with Special Reference to the Oriskany and Camden Formations. By Charles Schuchert	665-670
Age and Development of Red Beds and Terrestrial Vertebrates of the Appalachian and Kansas-Texan Sections. By J. W. Beede	671-688
Strata Near Stuart, Iowa. By John L. Tilton	689-702
Front Ranges of the Andes Between Santa Cruz, Bolivia, and Embarcacion, Argentina. By Kirtley F. Mather	703-764
Deccan Traps and Other Plateau Basalts. By H. S. Washington	765-804
Some New Facts Bearing on Correlations of Chester Formations. By E. O. Ulrich	805-852
Index to Volume 33	853-862
Title page, Contents, etcetera, of Volume 33	i-xxi

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA

Subscription, \$10 per year; with discount of 10 per cent to institutions and libraries and to individuals residing elsewhere than in North America. Postage to foreign countries in the postal union, forty (40) cents extra.

Communications should be addressed to The Geological Society of America, 77th Street and Central Park, West, New York City, or care of Florida Avenue and Eckington Place, Washington, D. C.

NOTICE.—In accordance with the rules established by Council, claims for non-receipt of the preceding part of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C.,
under the Act of Congress of July 16, 1894.

Acceptance for mailing at special rate of postage provided for in Section 1103,
Act of October 3, 1917, authorized on July 8, 1918.

DEVONIAN OF OKLAHOMA, WITH SPECIAL REFERENCE TO
THE ORISKANY AND CAMDEN FORMATIONS¹

BY CHARLES SCHUCHERT

(Read before the Society December 28, 1921)

CONTENTS

	Page
Introduction.....	665
Oriskany of Marble City.....	666
Oriskanian of Arbuckle Mountains.....	667
Middle Devonian.....	668
Chattanooga shale.....	669
Section of the Devonian near Marble City, Sequoyah County, Oklahoma..	669

INTRODUCTION

The various discoveries of the Lower Devonian formations in western Tennessee were recounted by Dunbar in 1919.² In 1913 Weller and Mehl announced before the Geological Society of America their remarkable find of Helderbergian and Oriskanian faunas in the limestones of Sainte Genevieve County, Missouri. This extended the known range of Oriskanian seas 500 miles, from southern Virginia to Missouri or from northern Lake Huron to Missouri. The presence of Helderbergian in Oklahoma has been known ever since J. A. Taff's description of it in 1902 in the Tishomingo Folio of the United States Geological Survey, but far more detail was given by Reeds³ in 1911. The Oriskany, on the basis of fossils, was, however, not clearly discerned by Reeds. Then came the discovery of the true Oriskany in western Tennessee by Dunbar (Quall and Harriman formations) in 1917, extending this sea 200 miles to the southward; and now the announcement not only of the Oriskany, but as

¹ Manuscript received by the Secretary of the Society January 6, 1922. This paper was read before the Society under the title "Oriskany of Oklahoma."

² C. O. Dunbar: Stratigraphy and correlation of the Devonian of western Tennessee. Bull. 21, Tennessee Geological Survey.

³ C. A. Reeds: The Hunton formation of Oklahoma. Amer. Jour. Sci. (4), vol. 32, pp. 256-268.

well of the Camden in Oklahoma, another extension of more than 300 miles.

ORISKANY OF MARBLE CITY

During the field season of 1919 Mr. D. K. Greger was studying the stratigraphy of northeastern Oklahoma for the Empire Fuel and Gas Company, and near Marble City collected a lot of fossils, as he thought, from the Saint Clair marble. These later on came to me without further comment. This marble is well known to have Middle Silurian fossils in its upper part, but Greger collected from it such characteristic Upper Oriskany forms as *Spirifer arenosus* and *S. munchisoni*. These left no doubt that the Oriskanian sea, as recorded in the white limestones of Sainte Genevieve County, Missouri, once extended unbroken across what is now the Ozark dome, at least 300 miles farther to the southwest. More information was asked for, but it soon became apparent that the locality must be revisited to study the position of these fossils in the local section. This was done at my request early in September, 1921, by Doctor Dunbar, and it is to him and to Mr. Greger that I owe thanks for this most interesting stratigraphic discovery. Not only is the presence here of Upper Oriskany now established, but as well a thin western sandy phase of the Camden of Tennessee, the oldest known American phase of the Middle Devonian.

In the limestone quarry near Marble City Dunbar collected a large piece of *Gyroceras elrodi* and another one of *Protokionoceras medullare*?, but these by themselves did not give me the exact age of the upper part of the Saint Clair marble. With other names they might pass as well for Helderbergian. In looking up the work of Taff in the Tahlequah Folio⁴ it was seen that from the upper part of this marble he had collected nine other species; and these, as identified by E. O. Ulrich, left no doubt that the Saint Clair marble in its upper part is of high Middle Silurian age. On the top of this marble follows from 5 to 8 feet more of the same kind of white limestone, and Dunbar noted that it was separated by an easily seen erosional unconformity from the Saint Clair marble. This is all that now remains here of the Upper Oriskany, but more must have been deposited and later worn away. This conclusion is supported by the erosional unconformity which follows and by the marked differences between the Oriskanian and Camden faunas. There is no Lower Oriskany present here, and, curiously, none of the Helderbergian, which occurs in considerable thickness in the Arbuckle Mountains, something like 150 miles to the southwest.

⁴ U. S. Geological Survey, Geological Folio No. 122, 1905.

The Upper Oriskany near Marble City has the same facies as that of Sainte Genevieve County in eastern Missouri, a white, coarsely crystalline limestone made up of fragmented and worn fossils cemented by pure carbonate of lime. This is an unusual facies of the Oriskanian for the United States, since in other places it is either a more or less coarse sandstone or a decidedly arenaceous limestone appearing in exposures as a porous sandstone. At Gaspé, Canada, the Oriskanian facies is also limestone. The former occurrences indicate that the Oriskanian sea of Missouri and Oklahoma, extending across the Ozarkian mass, was a warm-water one, and received almost no detrital material from the adjacent lands. Nevertheless, the faunas of these southern places are very similar to those of the northeast. Some of the conspicuous species of the northern faunas, of sandy facies, as *Edriocrinus sacculus*, *Hipparionyx proximus*, *Chonostrophia complanata*, the very large *Plethorhynchus*, *Rensseleria ovoides*, and *Phacops* and *Homalonotus*, are all absent in the limestone phase of the southern seas.

ORISKANIAN OF ARBUCKLE MOUNTAINS

In 1911 Reeds described the Bois d'Arc thin-bedded crystalline limestone of the Arbuckles, a formation varying in thickness from 0 to 90 feet, with a general average of 60 feet. He then thought it to be more nearly equivalent to "the Becraft than the New Scotland of the New York section," but added: "It may yet be determined that the uppermost 40 feet of the Bois d'Arc are Oriskany in age." He held that deposition with the Helderbergian was continuous, and listed twenty-three species, the following of which are Oriskanian forms: *Favosites shriveri*, *Cyrtina rostrata*, *Eatonia singularis*, *Plethorhyncha præspeciosa*, *Leptostrophia magnifica*, *L. oriskania*, *Meristella lentiformis*, and *Rensseleria marylandica*. Because of the absence of guide fossils like *Spirifer arenosus* and *S. murchisoni*, we then concluded that the Bois d'Arc was not of Oriskany time, since it had a large number of Helderbergian species. It is now clear that this terminating limestone of the Lower Devonian of the Arbuckles is also of Oriskanian age, and that in all probability the Bois d'Arc does not pass unbroken into the Helderbergian (Haragan), as was then supposed. Here also all of the Lower Oriskanian is absent. Evidently the Arbuckles area lay more nearly in the center of the marine basin and therefore had a far greater thickness of Oriskanian limestone and a longer differentiating fauna, while to the northeast and nearer the shore the deposition was far less, though the present thickness of from 5 to 8 feet may be only a remnant of a much thicker series of limestones.

MIDDLE DEVONIAN

In the region of Marble City the thin Oriskanian is followed by the Sylamore sandstone, of which Dunbar saw a thickness of about 5 feet. Taff, on the other hand, in his Tahlequah Folio speaks of the Sylamore as being variable in thickness, and says that in the vicinity of Marble City it is between 20 and 30 feet thick, followed by about 20 feet of Chattanooga shale. While in the field, Dunbar measured 50 feet of black shale; so that between them there is no discrepancy as to thickness. We may therefore say that there is of the Sylamore sandstone at least 5 feet, but that there may be between 20 and 30 feet. Taff notes further, however, in places farther north, that the next higher formation, the "Chattanooga black shale," rests directly on the Saint Clair marble of Middle Silurian age. It is plain, therefore, that the whole of the Sylamore may be locally absent, and that this absence is not due to a lack of deposition as a sandstone lentil of the Chattanooga, but to erosion. This is made clear by the following statement from Taff. The Sylamore sandstone, he says, "terminates abruptly at the top in Walkingstick Hollow [only a few miles to the northwest of Marble], where the contact is clearly exposed. At one locality noted in this valley, where the erosion of the stream had just reached the top of the sand, the surface is uneven, the black shales filling irregular depressions a foot and less in depth and 2 to 3 feet in width. The contact between the shale and the sand is clean, no sand being included in the shale, even in the basin-like depressions" (page 3).

Dunbar was so fortunate as to find some characteristic brachiopods in loose blocks from the basal 5 feet of the Sylamore sandstone, and they are all forms of the Camden, a formation once regarded as of Oriskanian age, but now known to be of earliest Middle Devonian time.⁵ These species are listed in the section described on a later page.

Taff, in the Tahlequah Folio, says the only fossils collected by him in the Sylamore sandstone are "more or less macerated fragments of large fish bones, apparently of the genus *Dinichthys*," and more rarely small fish teeth. As the bones of the "terrible fish" are more often found in the Upper Devonian, he concluded that the Sylamore was a sandstone lentil, followed without break by the "Chattanooga black shale," and that both are of late Devonian time. However, as fish bones are common in the Onondaga and as *Dinichthys* also occurs here, it is seen that this evidence for age determination is not so reliable as the brachiopods, all of which are of Camden species or of earliest Ulsterian time.

⁵ Dunbar: Op. cit., pp. 88-90.

CHATTANOOGA SHALE

The Sylamore sandstone is overlain unconformably by the "Chattanooga black shale," variable in thickness in the Tahlequah quadrangle up to at least 40 feet, this variability being due to another erosion interval following the deposition of the shale. The age of this formation is unknown, since no fossils have been found in it in the Tahlequah quadrangle. It may be of late Devonian or early Mississippian (Kinderhook) time.

SECTION OF THE DEVONIAN NEAR MARBLE CITY, SEQUOYAH COUNTY,
OKLAHOMA

The following section is made up in the main from the hillside (Quarry Hill) due northwest of the marble quarry and the hillside to the northeast of the quarry. The region is a little more than one mile to the north of Marble City and on the northwest side of Sallisaw Creek:

Lower Mississippian.

Boone chert (= Keokuk).

Marked break in deposition, no Saint Joe being present.

Upper Devonian or early Kinderhook.

"Chattanooga black shale," 20 to 40 feet thick.

As no fossils are known from this formation, its age is uncertain.

Break. North of the marble quarry in Walkingstick Hollow, Taff describes the sequence as broken and the contact as sharp between the shale and sandstone.

Middle Devonian.

Sylamore sandstone = Camden chert of western Tennessee. At least 5 feet thick, but from Taff's description attains to 20 and even 30 feet thick. The basal 5 feet are a white to brown, coarse quartz sandstone, muddy, cemented with more or less of carbonate of lime, weathering a rusty brown. From loose blocks scattered over this formation were obtained *Leptæna rhomboidalis ventricosa* Hall, *Schuchertella* (new large species), *Spirifer worthenanus* Schuchert, and *Amphigenia curta* (Meek and Worthen). Taff reports the presence of the bones of *Dinichthys* and small teeth of fishes.

Probable break in deposition.

Lower Devonian.

Upper Oriskanian white limestone. From 5 to 8 feet of a fossil coquina of fragmented and worn fossils cemented by a coarsely crystalline carbonate of lime. Fossils are common, but are hard to get because of the massiveness of the limestone. Those marked with an asterisk also occur in Missouri in a very similar limestone. *Favosites shriveri*, F. (large ramose form), large crinoid stems, *Fenestella* two species, *Trepostomata*

bryozoans, *Rhipidomella musculosa* (Hall), **Leptæna rhomboidalis ventricosa* (Hall), **Leptostrophia oriskania* Clarke, *Stropheodonta vascularia* Hall, *Strophonella* sp., **Eatonia peculiaris* (Conrad), **Plethorhyncha præspeciosa* Schuchert, *Delthyris raricostus* (Conrad) ?, **Spirifer arenosus* (Conrad), **S. murchisoni* (Castelnau), *S. n. sp.* in line to *S. divaricatus*, *Meristella lata* Hall, **Rensselæria marylandica* Hall, *Orthonychia tortuosum* (Hall), *Dalmanites* (*Odontocephalus*).

An easily seen erosional unconformity is shown in Sallisaw Creek.

A long land interval. All of Helderbergian strata absent and all of Upper Silurian.

Middle Silurian.

Saint Clair marble or Sallisaw marble of Taff. At least 60 feet of a massive, coarsely crystalline limestone is exposed in the marble quarry, and Taff states that the total thickness exceeds 200 feet. Almost no bedding planes are seen in the quarry, and here were collected a specimen each of *Gyroceras elrodi* Hall and *Protokionoceras medullare* Hall? Taff lists nine other species from the upper part of the Saint Clair that indicate the time of this portion to be later Middle Silurian.

AGE AND DEVELOPMENT OF RED BEDS AND TERRESTRIAL
VERTEBRATES OF THE APPALACHIAN AND
KANSAS-TEXAS SECTIONS ¹

BY J. W. BEEDE

(Read before the Paleontological Society December 28, 1922)

CONTENTS

	Page
Introduction.....	671
Correlations.....	671
Succession of the invertebrates and correlation of their horizons.....	671
Succession of the floras and correlation of their horizons.....	676
Succession of the vertebrates and correlation of their horizons.....	679
Review of conditions <i>versus</i> time hypothesis.....	682
Age of the Appalachian and the western red beds.....	684
Conclusions.....	687

INTRODUCTION

A study of the Upper Pennsylvanian and Lower Permian stratigraphy and fossils has been in progress by the writer for some time. This study has involved the correlation of the beds of these systems over North America and Eurasia, in so far as that is possible. It has particularly involved the correlation of the Appalachian and western sections, and in view of some novel suggestions that have been made to account for the peculiar distribution of the fossil air-breathing vertebrates, it is thought that the results of this work may be of interest.

CORRELATIONS

SUCCESSION OF THE INVERTEBRATES AND CORRELATION OF THEIR
HORIZONS

The invertebrate fauna of the upper part of the American Pennsylvanian has certain characteristics. For instance, the fauna, as a whole,

¹ Manuscript received by the Secretary of the Society June 10, 1922.

Published with the permission of the Director of the Bureau of Economic Geology and Technology, University of Texas.

possesses unity of expression and is characterized by relatively little evolution when the great length of time involved is considered. The larger formations, or stages, are characterized by the introduction of a few distinctive species and the extinction or disappearance of others, together with the fact that certain persistent forms found throughout great thicknesses of strata become very abundant in certain horizons. A number of species run the gamut of the formations of the middle and upper parts of the Pennsylvanian.

The data on which these generalizations are based is shown in detail for the Kansas section in volume IX of the University of Kansas Geological Survey Reports.²

A glance at the Kansas faunal chart shows a continuous diminution of the number of species in the formations after the Oread limestone, the top of the Douglas stage, is passed. Many new forms are introduced in the higher formations shown on the chart. If still higher beds in the Kansas-Oklahoma succession had been included, the number of added species would have been considerably larger.

Subsequent to the publication of this work, data became available which made it advisable to consider the base of the Neva limestone as the base of Series IV, the base of the Permian, instead of the base of the Elmdale formation. This increases the number of species found in Series III by those that are first recorded in the Elmdale formation and diminishes the number found in Series IV, namely, a loss of ten species to Series IV and the addition of eight species to Series III. Since the chart was completed additional work in Oklahoma has added somewhat to the fauna that is accredited to Series IV, to a considerable extent by the addition of species not known from the formations below it. The numerical relationships of the species has been discussed elsewhere.³

Similar detailed charts were prepared by Miss Mark for the fauna of the Conemaugh formation of Ohio,⁴ in which the Ohio faunas are compared and correlated with those of the Kansas section. The lower Conemaugh formation of Ohio is more typically marine in Ohio than in West Virginia and possesses a correspondingly richer fauna, Miss Mark's lists containing 168 species. This fauna is strictly Pennsylvanian in its characters, and Miss Mark correlates its highest horizon, the Ames limestone, approximately with the Oread limestone of the Kansas section, and its

² Beede and Rogers: Faunal studies of the Kansas Coal Measures. Univ. of Kans. Geol. Survey, vol. ix, 1908, pp. 318-385. See especially the chart facing page 328.

³ Jour. Geol., vol. xvii, 1909, pp. 710-729.

⁴ Clara G. Mark: Fossils of the Conemaugh formation in Ohio. Ohio Geol. Survey, 4th series, Bull. 17, 1912, pp. 261-326.

lowest member, the Brush Creek bed, with the middle of the Pottawatomie formation.

The first correlation, that of the Ames limestone with the Oread limestone, or possibly the base of the Shawnee formation, is in complete agreement with the writer's conclusion, based on the fauna as represented in West Virginia.

However, the writer made no attempt to correlate the lower Conemaugh with the Kansas section. Miss Mark places the lowest fossiliferous beds of the Conemaugh, the Brush Creek, approximately on a level with the middle of the Pottawatomie formation. That would probably be somewhere in the upper part of the Kansas City formation. However, the Brush Creek does not constitute the base of the Conemaugh, but is from 80 feet to a much greater height above it. Neither is the middle of the Pottawatomie the base of the Kansas beds supposed to rest on the top of the Allegheny, or Des Moines, of Kansas. This interval is larger in Kansas than it is in Ohio and West Virginia, but is insufficiently so to seriously influence the results attained in this paper; that is, *for our present purposes*, that difference is negligible.

The size and character of the Conemaugh fauna is such as to make its place in the Kansas succession fairly certain. It is quite certain that it does not belong much higher in the Kansas section than the place assigned to it, since the most of the fauna is characteristic of Series II, and possibly some of it the basal part of Series III, but none of it is characteristic of Series IV, the beds referred to the basal Permian.

Consequently the remainder of Series III is left for the non-marine Conemaugh and the Monongahela formations—that is, the upper part, or most of the Shawnee and the Wabaunsee stages, as limited elsewhere in this paper.

Leaving the Pennsylvanian part of the section, with its long-lived species and sluggish development of forms, and turning to the higher beds, we face a different set of conditions.

Thus, the Fusulinæ at the base of Series IV branched in two directions. One of these developed the true Schwagerinas in Kansas and Texas, and another into long, slender, complicated Fusulinas, found in other regions, quite different from the regular, tiny, fusiform species which characterize the Pennsylvanian, though a few of the latter persist into the basal Permian. Higher up, elsewhere in the Permian, these elongate forms attain gigantic proportions for Paleozoic Foraminifera, as one specimen, preserving hardly half its length, must have been over 50 millimeters long and 5 millimeters in central diameter.

West Virginia- Pennsylvania.		Kansas.		Texas.
		Wellington.	Wellington.	
Dunkard.	P E R M I A N. Series V.	Marion.	Pearl shale. Herrington limestone. Enterprise shale. Luta limestone.	Wichita.*
		Chase.	Winfield limestone. Doyle shale. Fort Riley limestone. Florence flint. Matfield shale. Wreford limestone.	
		Council Grove.	*Neosho form. } Garri- Florena shale. } son. Cottonwood limestone. Eskridge shale. Neva limestone.	
Monongahela.	Series III. M i s s o u r i a n.	Wabaunsee.	Elmdale formation. Americus limestone. Admire shale. *Emporia limestone. Willard shale. Burlingame limestone. Scranton shale.	Cisco.
		Prosser in 1895.		
		Shawnee.	Howard limestone. Severy shales. Topeka limestone. Calhoun shales. Deer Creek limestone. Tecumseh shales. Lecompton limestone. Kanwaka shale.	
		Douglas.	Oread limestone. Lawrence shale. Iatan (Kockapoo) lime- stone. Weston (Le Roy) shale.	
Conemaugh.	Series II. P E N N S Y L V A N I A N.	Lansing.	Stanton limestone. Vilas shale. Plattsburg (Allen) limestone. Lane shale.	Canyon.
		Kansas City.	Iola limestone. Chanute shales. Drum limestone. Cherryvale shale. Winterset (Dennis) limestone. Galesburg shale. Bethany Falls lime- stone. Ladore shale. Hertha limestone.	
		Pleasanton.	La Cygne shale. Lenapah (Coffeyville) limestone. Nowata (Walnut) shale. Altamont limestone. Bandera shale.	
		Henrietta.	Pawnee limestone. Labette shale. Fort Scott limestone.	
Allegheny.	Series I. Des Moines.	Cherokee.	Cherokee shale.	

* = vertebrate fossils.

In the top of the Gaptank formation and in the Wolfcamp beds of West Texas, which lie in a part of the Permian geosynclinal basin, the Schwagerina fauna contains the beginnings of the typical Lower Permian fauna in such forms as *Fusulina* aff. *longissimoides*, *Schwagerina*, two species; *Enteleutes oehlerti* Gemm. *Geyerella?* sp., *Productus guadalupensis comancheanus* Girty, *Euomphalus* aff. *ponderosus* M. and W., *Omphalotrochus*, two species. In the Wolfcamp are twelve species of Ammonoids, described by Böse, which possess Permian affinities, together with *Cladopora?*, *Leptodus*, and *Aulosteges*, aside from those already enumerated. As a rule, it is characteristic of a number of Permian invertebrate forms to show a marked increase in size over Pennsylvanian species. There is also a tendency for many of them to take on specialized and even bizarre forms. Some of these fossils have been mentioned above and others occur in higher beds, such as *Leptodus*, *Richtofenia*, *Aulosteges*, and other forms described by Girty,⁵ together with such Ammonoids as *Waagenoceras*, *Perrinites*, *Adrianites*, *Medlicottia*, *Paraceltites*, *Stacheoceras*, etcetera, described by Böse.⁶

From these data it is apparent that the Schwagerinas occur at nearly the same horizon as the known beginning of the Permian ammonoids and in the same beds with other known Permian invertebrates. Based upon its invertebrate fauna, the Neva limestone of Kansas, with its Schwagerina fauna, may be regarded, in the light of our present knowledge, as forming the base of the Permian beds in Kansas, and the Schwagerina beds of the same age in West Texas may likewise be regarded as marking the base of the Lower Permian beds there.

The top of the Cisco in northern Texas reaches practically to the base of the Schwagerina beds, though species of this genus have not yet been found there. Evidences of unconformity have been observed at this level by at least three experienced geologists, though, so far, no publication to that effect has come to hand. Confirmatory to these observations is the fact that the usual *Fusulina* succession occurs to the upper Cisco where the more obese *Fusulinas*, precursors of the Schwagerina fauna, are found; but above these beds no Schwagerinas have been found, though they occur in the Hueco and Marathon regions to the southwest and in the Kansas-Oklahoma region to the north. It would thus seem that the region now occupied by the outcrop of the top of the Cisco and base of the Wichita beds that rocks of Schwagerina stage were not deposited or that they were removed by erosion after deposition. However, it is more

⁵ Guadalupian fauna. U. S. Geol. Survey Prof. Paper 58.

⁶ The Permo-Carboniferous ammonoids of the Glass Mountains. University of Texas Bulletin 1762, January, 1919.

likely that conditions were unfavorable to them. At the same time it is possible that this fauna exists there, but has not been collected, though it hardly seems probable.

In the light of the foregoing evidence it would seem that, so far as the evidence furnished by the invertebrate faunas of the Appalachian and western interior regions, the successions are not difficult to correlate. In the second place, that the evolution of the faunas was slow until the base of the Neva limestone or its equivalents elsewhere have been approached, when the evolutionary processes were remarkably quickened and new faunas were developed.

SUCCESSION OF THE FLORAS AND CORRELATION OF THEIR HORIZONS

On account of the widely distributed plant beds in the Pennsylvanian and the Permian systems, the record of the floras of these periods is of great value for purposes of correlation, and it will be interesting to compare correlations based on these floras with correlations based on the invertebrates.

In the Appalachian region above the Pottsville series, the flora is well known nearly to the top of the Conemaugh, and is the type section for comparison of upper Pennsylvanian floras of America. Without going into too great detail, it may be stated that the post-Pottsville plants fall into two groups, as found in the Allegheny and Conemaugh stages respectively. Skipping the uppermost Conemaugh and Monongahela series, the flora of the Dunkard series of the lower Permian has also been rather fully described.

Beginning with the Cherokee formation of Kansas and Missouri, the lowest Pennsylvanian formation occurring in the State of Kansas, we find a flora which was described by White⁷ as Allegheny in age. This Allegheny flora extends upward to the unconformity in the upper part of the Pleasanton shales. In other words, it corresponds with the Des Moines stage of the western Mississippi Valley.

Concerning this flora, White remarks:

"The Lansing [Cherokee shales] horizon is certainly not lower than, and probably not so low as, the lower coal-bearing division of the Arkansas Coal Measures. . . . The flora seems to correspond to that of the Middle Coal Measures of Great Britain and to the uppermost portion of the latter or to the transition series above the Westphalian of the continent of Europe."⁸

Speaking of the flora of the Le Roy (Weston and Lawrence) shales of Series III of Kansas, he states:

⁷ David White: U. S. Geol. Survey Monograph xxvii, 1899.

⁸ U. S. Geol. Survey Bulletin 421, 1903, p. 111.

"From such material as I have examined from this horizon, I am disposed to regard its stage as more strongly marked by the large Pecopterids, including callipteridoid forms, by the broad Allethopterids and the dilated Neuropterids. The presence of *Allethopteris grandini*, *Annularia sphenophylloides* var. *intermedia*, which is very closely related to *S. filiculme*, seems to point toward a level possibly as high as the Pittsburgh coal in the Monongahela formation. But the presence of the forms which, so far as known, appear to include a lower stage makes it seem improbable that the Lawrence plants are of quite so late a date as the Monongahela formation of the Appalachian trough."⁹

In short, they appear to belong to the upper part of the Conemaugh formation.

One of the critical floras to be compared with the plants of the Appalachian section is the flora from Onaga, Kansas, found in the Elmdale formation. Concerning these plants White states:

"Nearly all the species have been reported from the Permian of Europe or the Dunkard formation of the United States, though, with the possible exception of *Pecopteris newberriana*, none are distinctly characteristic of the Permian. It would seem that the Onaga flora should be of later date than the Pittsburgh coal. The evidence presented by this small Onaga flora may, therefore, be construed, so far as it represents the plants of its horizon, as indicating a stage probably within the Monongahela formation of the Appalachian region, or possibly as high as the lowest part of the Dunkard formation, although, with the exception of *Pecopteris newberriana*, the collection in hand does not contain any species characteristic of the Permian of the old world and does not signify the Permian age of the Onaga (Elmdale) beds."¹⁰

That is, plants typical of the Pennsylvanian formations are absent from this local flora, and its whole composition, aside from the one species quoted, is made up of the persistent or transition forms that pass over into the basal Permian.

The next formation above the Elmdale is the Neva limestone, which carries a Schwagerina fauna and forms the base of the Schwagerina zone of the western part of the Hydrographic basin of the Gulf of Mexico. The top of this zone is found in the Florence flint. Somewhat above the middle of this zone is the Wreford limestone, which is composed of two thick beds of cherty limestone separated by a parting of shale which contains fossil fish, land plants, and ostracods.

In this shale parting White made a collection of fossil plants, regarding the age of which he states:

"An inspection of the rather short list from the Wreford limestone reveals a flora most of whose species are characteristic of the Permian, a small per-

⁹ Ibid., p. 114.

¹⁰ Ibid., p. 116.

centage only being common to the Coal Measures. It is, in fact, somewhat surprising to note so few pre-Permian forms in this flora.”¹¹

In the paragraph quoted, there is a discussion of a list of plants found north of Washington, Washington County, Kansas, with a considerable number of Pennsylvanian survivors, concerning which an explanation is necessary.

The apparent horizon of this locality, as belonging to the Winfield limestone, was given to White by the present writer. It is virtually an inlier in the Cretaceous rocks of the region and its position in the Permian section was inferred from its geographic position with respect to rocks outcropping farther east. Recently it has been found that one of the buried granite ridges of this part of the State is located in this region,¹² so it is likely that the apparent age of this exposure was underestimated on account of the presence of a large anticlinal fold the top of which had been eroded away. Its actual horizon is unknown.

From beds higher than the Neva limestone, in Kansas, we have 21 genera, represented by 50 species, concerning which White remarks:

“All the specially identified plants [eliminates five species] in the above list are found in beds referred to the Permian in their respective provinces, most of them being European. The species in bold types [33] are diagnostic of the Permian.”¹³

In Oklahoma and Texas, in the beds which possibly are above a large part of the Kansas beds, from which the plants just referred to occur, we find a *Gigantopteris* flora introduced. This flora contains 18 genera and 46 species, practically all of which are either diagnostic of the Permian or occur in Permian beds of other parts of the world.¹⁴

From the foregoing data it is seen that in the case of the plants those characteristic of the Pennsylvanian continue nearly to the Neva limestone, when they disappear, except for certain persistent or transition elements which go over into the Lower Permian deposits, as is typified by the *Onaga* flora.

In this respect the whole history of the plants parallels that of the invertebrates, except that the species and genera of the latter are, on the whole, more persistent than are the species and genera of the plants.

In both cases the evolution of genera and species was relatively slow during the Pennsylvanian and was quickened with the initiation of the Permian conditions. They show apparently autochthonous genera and

¹¹ Proc. U. S. Nat. Mus., vol. xli, 1912, p. 509.

¹² Moore: Bulletin Amer. Assoc. Pet. Geol., vol. iv, 1920, map, p. 257.

¹³ D. White: Proc. U. S. Nat. Mus., vol. xli, no. 1873, 1912, pp. 508, 509.

¹⁴ D. White: Op. cit., pp. 505-507.

species, together with immigrants from other regions.¹⁵ The conditions responsible for this rapid development accomplished the rapid elimination of the Pennsylvanian forms.

In the light of the evidence furnished by the fossil plants, namely, that all the typical Pennsylvanian species had been removed from the Onaga flora, leaving only those that persist into the Permian, and the presence of a well developed Permian flora in the Wreford limestone, it would seem that the Permian flora first appeared in an intermediate formation, more likely quite as near to the lower as to the upper horizon.

Similarly, faunal elements begin to appear in the Elmdale formation, which persist into the Permian, and Schwagerina and its accompanying fauna appear in the Neva limestone. Hence the line between the Pennsylvanian and Permian periods is placed at the base of the Neva limestone.

From the review of the fauna and the flora characterizing the Western and Eastern sections, it is found that the correlations based on the two types of evidence is not seriously discordant. Indeed, it is nearly as harmonious as one might expect for correlations based on marine invertebrates and on land plants, and there appears to be little reason to question these correlations, though the correlation based on the fossil plants would place the Conemaugh formation lower in the Kansas section than that based on the invertebrates. For present purposes, the difference is negligible.

SUCCESSION OF THE VERTEBRATES AND CORRELATION OF THEIR HORIZONS

With this history of the range and distribution of the invertebrates and plants of the latest Pennsylvanian and basal Permian beds in mind, it is interesting to turn to the analysis of the occurrence of the vertebrates which existed during the same periods of time. The following table shows the distribution of the vertebrates in the Appalachian and Western section:¹⁶

¹⁵ D. White: Jour. Geol., vol. xvii, 1909, p. 335.

¹⁶ Case: Carnegie Institution of Washington, Publication No. 107, 1915.

Moodie: Carnegie Institution of Washington, Publication No. 238, 1916.

Genera and species of Amphibia.		Genera and species of Reptilia.		Locality and horizon.
Genera.	Species.	Genera.	Species.	
<i>Permian</i>				
16	26	27	41	Texas, Clear Fork.
11	15	23	35	Oklahoma-Texas, Wichita.
—	—	—	—	
Total.....	22	35	57	
<i>Pennsylvanian</i>				
1	1	1?	1?	Kansas, Louisville, base of Elmdale?
4	6	3	3	Illinois, Danville, Conemaugh?
1	1	2	2	West Virginia - Pennsylvania, Conemaugh.
23	51	1	1	Linton, Ohio, top of Allegheny.
10	17	0	0	Nova Scotia, top of Allegheny?
8	10	0	0	Mazon Creek, Illinois, base of Allegheny? or top of Pottsville.
—	—	—	—	
Total.....	47	7	7	

Of the genera of Pennsylvanian Amphibia, four continue into the Permian, as do three of the seven genera of Reptilia.

From this table it is apparent that the first known vertebrate fauna was a purely amphibian fauna, from the basal Allegheny or top of the Pottsville. The first known reptile, *Eosauravus*, occurs in the Linton coal of Ohio, in the top of the Allegheny series. Later two reptilian forms are known from the Conemaugh of Pennsylvania and West Virginia, and three are known from the Danville, Illinois, beds of uncertain age. It is at present impossible to ascertain with certainty the age of these last beds. However, the writer is of the opinion—largely unsubstantiated as yet—that the Danville material is of no later age than the Conemaugh, but fortunately it preserves a somewhat more complete picture of the air-breathing vertebrates of that time than do the Pennsylvania-West Virginia remains. There is also one amphibian and probably a reptile from the upper Pennsylvanian of Kansas. The wealth of material from Nova Scotia described by Dawson is probably very near the horizon of the Linton, Ohio, fauna.

In all these Pennsylvanian forms there are 47 genera and 86 species of Amphibia known from the Pennsylvanian and only 7 genera and 7

species of reptiles known from the same system of sediments. From this it is seen that the Pennsylvanian fauna is a distinctly amphibian fauna, 91 per cent of its genera being unknown in rocks higher than the Neva limestone; 50 per cent of the Reptiles go over into the beds higher than the Neva limestone.

In contrast with this condition we find in beds above the horizon of the Neva limestone (none of the beds within about 100 feet of it are known to contain air-breathing vertebrate remains) a very different relation of the two classes of animals. Thus there are only 22 genera and 39 species of Amphibia in these higher beds, while there is a total of 35 genera and 57 species of reptiles, which constitute a distinctly reptilian fauna in contradistinction to the amphibian fauna of the Pennsylvanian.

Taking the fauna in detail by formations, or stages, we find in the Wichita beds and their equivalent in Oklahoma 11 genera and 15 species of Amphibia, of which only four genera have come up from below, while there are 18 genera and 36 species of reptiles known from this stage, only three of the genera having persisted from the Pennsylvanian beds, leaving 15 out of the 18 genera introduced during the Wichita stage.

In the Clear Fork beds there are 16 genera of Amphibia, represented by 26 species—an increase in numbers over those known from the Wichita stage, but still below the Pennsylvanian numbers. The Clear Fork Reptilia are represented by 27 genera and 41 species, showing a marked and consistent increase over those from the Wichita beds.

This fact in itself is a very significant illustration of the faunal changes brought about during earliest Permian time. However, if we take into account the extensive specialization of many of the Permian reptiles, such as *Dimetrodon*, *Celapsydrops*, and others, the case comes to have far greater significance. To sum up the history of the air-breathing vertebrates of the Pennsylvanian and Permian, we start with a pure Amphibian fauna in the lower Allegheny, extending to the upper Allegheny, and a mixed Amphibian-Reptilian fauna above this horizon, with the Amphibia in overwhelming preponderance to the base of the Permian, when the Reptilian forms preponderate and are extremely specialized.

From the data at hand it is apparent that, so far as our knowledge goes, the air-breathing Vertebrata show very much the same history for the periods of time under consideration as do the invertebrates and the plants.

When measured in the terms of western sedimentary deposits, these fossils are distributed through some 5,000 or more feet of deposits nearly equally divided between the Pennsylvanian and Permian rocks, composed of shales, limestones, sandstones, and coals. The fauna clearly shows two distinct facies in the lower and upper part of these beds.

The fact that the earlier vertebrates are now known only from the eastern region and the highly specialized forms are confined to the western deposits demands consideration, as does tentative suggestions thrown out by Case,¹⁷ to account for this distribution.

REVIEW OF CONDITIONS VERSUS TIME HYPOTHESIS

The main idea in Case's suggestion is that the Appalachian region began to emerge early in Pennsylvanian, or even Mississippian, time, and that the process was continuous until the whole of the eastern and central United States became a land area, at the close of the "Permo-Carboniferous." It is also postulated that a local climatic change occurred at the inception of this movement and continued to its consummation, finally migrating westward with the emerging land.

He distinctly states this hypothesis in an article entitled "Permo-Carboniferous Conditions *versus* Permo-Carboniferous Time."¹⁸ In another place he described at length the supposed climatic and physical conditions, the faunas, and their vertical range and geographic distribution.¹⁹

Regarding the data on which the hypothesis is based, he states:²⁰

"The lower limit of the fauna is confessedly vague and shadowy, passing far down into the Pennsylvanian. The Pennsylvanian amphibians described by Moodie in numerous papers are so close to those occurring in association with the Permo-Carboniferous forms from Texas that it is evidently a case of overlapping, and the only recognizable line is that where the first reptile occurs. It is, of course, probable that the reptiles occurred at lower horizons. In 1910 Moodie found a form near *Cricotus* in the Mazon Creek shales. These shales occur near the base of the Allegheny (or top of the Pottsville). David White regards them as the equivalent of coal No. 2 of Illinois (Morris and Braidwood coals of the Clarion). They are regarded by him as having close relationship with the Cherokee of Henrietta County, Missouri, at the base of the Allegheny."

"The Linton coal, from which comes *Eosaurus copci* Williston, . . . belongs to the Upper Freeport coal (coal No. 6.), and is referred by Prosser to a position near the top of the Allegheny. . . . Williston and Moodie have described the genus *Eosaurus*, giving figures, and demonstrated its reptilian nature.

"The earliest amphibians definitely comparable to the Texas fauna are from the Pittsburgh red shale. The Pittsburgh red shale lies 300 feet above the Freeport coal and 695 feet or more below the base of the Dunkard."

"The exact age of the beds in Illinois (Danville) and Prince Edward Island, in which similar forms occur, is not yet determined."

¹⁷ E. C. Case: Permo-Carboniferous conditions *versus* Permo-Carboniferous time. Jour. Geol., vol. xxvi, 1918, pp. 500-506.

¹⁸ Jour. Geol., vol. xxvi, 1918, pp. 500-506.

¹⁹ Carnegie Institution of Washington, Publication 207, 1915.

²⁰ Op. cit., pp. 93-99.

"The limit recognized for the Permo-Carboniferous fauna is, then, from the Pittsburgh red shales to the top of the Clear Fork. The stratigraphic extent of the space delimited it is impossible to state, since there is no direct correlation of the eastern and western beds possible, but may be roughly stated as from the middle of the Conemaugh to the top of the Permo-Carboniferous. The limits of the fauna in America, however, are not those of Europe; the fauna there are continued into the Triassic."

In order to get a clear understanding of the whole subject, which can not be fully reviewed here, the two articles should be read in full.

After discussing the red beds and their fossil remains as local evidence of the gradual elevation of the Appalachians, he states:

"These local proofs of elevation are but contributory evidence of the whole eastern part of North America, probably as a continuation of the same movement which formed the Hercynian somewhat earlier in central Europe. The elevation of North America, which began on the eastern side, was gradually extended to the west, as is shown by the progressive disappearance of the Mississippian sea and the Pennsylvanian coal swamps in that direction.

"The elevation was attended by gradual change in climate; instead of gray and black shales and white sandstones the prevailing deposits were colored red by the oxidation of iron under the influence of a less equable climate, as seasons of relative drought and humidity succeeded each other.

"As the climatic change migrated toward the west only slowly, red sediments were formed at progressively higher and higher levels. In western Kentucky, Indiana, and Illinois the conditions necessary for the formation of red beds did not arrive until after the highest sediments now preserved had been formed, or only thin deposits were formed which have since been removed by erosion. That the surface of these regions was dry land by the time 'Permo-Carboniferous conditions' had reached them is suggested by the mode of occurrence of the vertebrates in Illinois and the Merom sandstone in Indiana." . . .

"Beyond the elevated region of Missouri, the upper Pennsylvanian and Permo-Carboniferous are limestones and gray to black shales, but farther south the Permo-Carboniferous beds of Oklahoma, Texas, and New Mexico are red. These beds lie above the Missourian of Missouri and Iowa which extend well up toward the top of the Pennsylvanian, as developed in Pennsylvania and West Virginia, certainly much higher than the first appearance of red beds in the Conemaugh of those States."

"As the uplift affected regions farther and farther to the west, the climate altered progressively in the same direction, and the resultant changes in physiography, hydrography, and vegetation compelled an alteration of the environment which permitted the migration of the Permo-Carboniferous amphibian-reptilian fauna with but little morphological change." . . .²¹

There are three phases of this postulate, the first two of which have been treated, to be discussed: First is the development of invertebrate, vertebrate, and plant life during the Pennsylvanian and early Permian;

²¹ Carnegie Institution of Washington, Publication 207, 1915.

the second is the correlation of the Appalachian and the Kansas-Texas sections; the third is the evidence of climatic change during the time concerned, and possible migrations of vertebrates and plants.

AGE OF THE APPALACHIAN AND THE WESTERN RED BEDS

If the facts thus far presented warrant the correlations made between the Appalachians and the western interior regions, it will be a simple matter to determine the relative age of the red beds of the two regions.

In the Appalachian region the oldest Pennsylvanian red beds are found a short distance below the Ames limestone, in the Conemaugh formation of West Virginia, Ohio, and Pennsylvania, and are known as the "Pittsburgh red shales" in the West Virginia Survey Reports. Lately this name has been replaced by the term Round Knob formation, since the term Pittsburgh was preoccupied for another formation, the Pittsburgh coal. It is in this formation that the vertebrates were discovered by Raymond and I. C. White. Regarding its thickness and vertical extent in Ohio Condit writes:

"The beds vary from structureless, purplish red clay to deep red, even-bedded shale, which may alternate with bluish layers. The more sandy portions frequently show ripple-marks and sun cracks."

"In the southern part of the State, where the Ames limestone is generally thin or wanting, the Round Knob red beds are continuous, with similar strata above the Ames horizon for many feet, and locally even reach nearly to the Pittsburgh horizon" [top of the Conemaugh].²²

From this it is plain that nearly the whole upper Conemaugh locally may be largely composed of red beds. The base of these beds is slightly below the middle of the formation, below which there are no true Pennsylvanian red beds.

In the various county reports of the West Virginia Geological Survey the detailed sections of the Conemaugh are given.

In some sections of the Dunkard in Pennsylvania the red beds seem locally to be nearly missing, while there are several beds present in other localities.²³

These red beds are unknown below the Round Knob or "Pittsburgh Reds" horizon of the Conemaugh. In the region south of the outcrop of the present Conemaugh formation nearly or quite all of the upper Conemaugh and perhaps much of its lower part would probably have been red had not these rocks been removed by erosion; so that it is impossible to

²² Condit: Ohio Geol. Survey, Bull. 17, p. 36, 1912.

²³ Data from West Virginia Geological Survey reports.

determine the position of what may have been the oldest red beds of the Appalachian region.

Turning now to the western section, we find the clearest record of the oldest red beds in Oklahoma, especially north of Arbuckle Mountains. On approaching Oklahoma and the Arbuckle Mountains from well up in southern Kansas, the strata are seen to become red as one goes south along the outcrops, and soon the stratigraphic level of the red beds grows lower and lower until Pottawatomie and Seminole counties are reached. The details and general principles of this color change and accompanying lithological facies of the deposits has been discussed by Gould in Water Supply Paper 148, and by Snider²⁴ and Beede,²⁵ and will not be repeated here.

Fritz Aurin prepared a paper on the Red Beds of Oklahoma,²⁶ in which he published a lithobathic map of the Oklahoma red beds showing their thickness by contours. In this article he discusses the depth to which the red beds are found in the Pennsylvanian rocks, and states:

"The red Pennsylvanian is a term applied to an undifferentiated series of sandstones and shales, predominantly red in color and very similar to the Permian red beds, occupying an interval between the non-red Pennsylvanian and the Neva limestone or equivalent horizon. . . .

"The red Pennsylvanian and Seminole conglomerate in a section across the northern part of Pottawatomie and Seminole counties is the approximate equivalent of the following named formations: Ladore shales, Mound valley limestone, Galesburg shale, Dennis limestone, Cherryvale shales, Drum limestone, Chanute shales, Iola limestone, Lane shales, Allen limestone, Vilas shales, Stanton limestone, Le Roy shales, Kickapoo limestone, Lawrence shales, Oread limestone, Kanwaka shales, Lecompton limestone, Tecumseh shales, Deer Creek limestone, Calhoun shales, Topeka limestone, Severy shales, Howard limestone, Scranton shales, Burlingame limestone, Willard shales, Emporia limestone, Admire shales, Americus limestone, and Elmdale formation. The thickness of the red Pennsylvanian and Seminole section is approximately 800 feet, while that of the equivalent Kansas section is 1,800 feet."

From this it is evident that the red beds began in the region north of the Arbuckle Mountains as early as the Bethany Falls limestone, or very near the base of the Missourian, which is fully as low, if not lower, stratigraphically than the base of the Round Knob formation of West Virginia and Ohio.

The similar transition of beds of sands and shales into red sediments in Texas is given by Gordon as follows:

²⁴ L. C. Snider: Bull. Okla. Geol. Survey, 1913, p. 11.

²⁵ Bull. Okla. Geol. Survey, 1914, p. 21.

²⁶ Bull. No. 30, Okla. Geol. Survey, 1917. Quotation from p. 23.

"A feature of importance in the Cisco formation, and one which it shares with the next formation, is the series of changes observed as the formation is traced northward along the strike. These changes relate both to changes in lithologic character and to thickness of beds. In the Colorado Valley, interstratified with sandstones, clays, and conglomerates, are six or more beds of limestone, each from 5 to 25 feet thick and all aggregating a thickness of 100 to 150 feet. In the southern part of the Brazos Valley the calcareous divisions are only about half as thick as they are farther south, and clays show a corresponding increase in thickness. In Young County the calcareous material diminished in thickness northward at an increased rate until, at the northern boundary of the county, the limestones have practically disappeared, and beyond that point they are represented apparently by irregular nodular masses of earthy limestone in a matrix of clay. With the thinning out of the limestones, the shales and sandstones increase in thickness. In Stephens County and farther south the shales are prevailing blue and the sandstones gray. Red beds are dispersed sparingly through the formation. The blues gradually give place to reds until in the vicinity of Red River the red color dominates. In this part of the region the rocks consist, for the most part, of red sandstones, clays, and sandy shales, with a few beds of blue shale and bluish to grayish white sandstones. Limestones are conspicuously absent."²⁷

The data here briefly summarized clearly show that the red sediments set in quite as early in the Arbuckle Mountain region, or north and south of it, as they did in the Appalachian region. Indeed, were all the Appalachian red beds still intact, there would be little reason to doubt that they would be found to be practically equivalent in age with the lowest of the red beds of the Pottawatomie-Seminole region and similar regions south of the Arbuckle Mountains.

For this reason it is apparent that it is unnecessary to postulate a different climate for the Appalachian region than that which existed in the western interior region.

Nevertheless, the fact that the red beds are as old in the western interior region as in the Appalachian Plateau does not explain the peculiar distribution of the vertebrates under consideration—that is, that the younger forms occur in the western region, while the older forms are known only from the region east of the Mississippi River. There are two factors bearing on this point that need to be discussed, neither of which is necessarily conclusive in itself, but between them they appear to include the probabilities of the case.

First. In the basal Permian, White, as quoted above, has shown that *Walchia* and some other plants are present in the western province while wanting in the eastern. This would imply that at the inauguration of the basal Permian the Appalachian region was isolated from the western region in such a manner as to prevent the intermigration of the plants.

²⁷ C. H. Gordon: U. S. Geol. Survey, Water Supply Paper 317, 1913, p. 18.

If this is true, it would likewise prevent the migration of the vertebrates which may have originated in the eastern province.

But to have prevented previous migrations it must be assumed that the regions were permanently separated by a water barrier from the late Pottsville to the upper part of the Wabaunsee stage, or about middle Monongahela time. This assumption is too sweeping to have much weight until further data are at hand on which to base it. A consideration which makes this proposition still more doubtful is the fact that species of plants of this interval are common to both regions.²⁸

Second. The alternate suggestion is that they existed contemporaneously in both regions, but as yet are known only from the eastern one, where detailed study of the formations has gone on for many years. There are three reasons why this supposition may be correct:

A. These forms would only be preserved under very special conditions and in isolated localities, and as a result relatively few of these forms were preserved, allowing only rare chance of being exposed at the present time, as is demonstrated by the extremely few vertebrate-bearing localities now known east of the Mississippi River, where the rocks have been more intensely studied. Therefore they may be present and not exposed in the western interior region.

B. They may well be present in formations in the west which are now exposed and have not been discovered. So far as known, no search for them has been made in the oldest red beds of Pottawatomie and Seminole counties. In this connection it should be mentioned that exposures in the red beds of the Wichita and Clear Fork stages are vastly more favorable for finding fossils than are more thoroughly vegetation-covered regions farther east, in the lower formations of Texas and Oklahoma.

C. The remains of an amphibian and a reptile were found in the Wabaunsee formation of Kansas, probably at about the level of the middle Monongahela stage of Pennsylvania and West Virginia. It is the writer's opinion that when the outcrops of the rocks have all been thoroughly searched for fossil air-breathing vertebrates, they will be found in western beds which are nearly as old as those from which they are known east of the Mississippi River.

CONCLUSIONS

1. It seems that the correlation of the eastern and western interior regions based on evidence of fossil animals and plants is well established. It is about as harmonious as might be expected from these two types of evidence.

²⁸ D. White: U. S. Geol. Survey Bull. 211, 1903, pp. 110-115.

2. The horizon of the Ames limestone is probably no higher than the top of the Oread limestone, and the top of the Conemaugh is at least as low as the top of the Shawnee stage, and that the Neva limestone is as high as the base of the Dunkard formation.

3. That marked changes in the fauna set in at the base of the Schwagerina horizon (Neva limestone).

4. In the formation below the Schwagerina horizon (Elmdale) only transition plants are known which go over into the Permian of Europe and America.

5. In the first known plant horizon above the base of the Schwagerina horizon (in the Wrexford limestone) the flora has a decided Permian aspect.

6. The vertebrate faunas older than the Schwagerina horizon are strongly Amphibian in character.

7. That the known vertebrate faunas above this horizon are strongly reptilian in character and they are even highly specialized.

8. The oldest known red beds of the Appalachian and western interior regions are almost equivalent in age, the latter apparently quite as old as the former.

9. The climatic conditions were essentially the same in both regions throughout Pennsylvanian time.

STRATA NEAR STUART, IOWA¹

BY JOHN L. TILTON

(Read before the Society December 28, 1921)

CONTENTS

	Page
Introduction.....	689
Area near Earlham and south of fault.....	691
Area near Earlham and northwest of fault.....	691
Contrasts on the two sides of fault.....	693
Area north of Stuart, along Deer Creek, north of fault.....	695
Area southwest of Stuart, along Middle River, north side of fault to fault-line.....	697
Position of the fault.....	698
Stratigraphic position of beds on the upthrow side of fault.....	698
Bearing of fault on position of coal and on lay of strata to the north.....	701
Bearing of fault on position of coal west of Stuart.....	701
Effect on the interpretation of deep-well records, and geological map of Iowa.....	701

INTRODUCTION

The Thurman-Wilson fault has already received some attention in the geologic literature of Iowa.² Todd recognized it close to Missouri River in 1889; Smith computed its throw (300 feet) at that point in 1909, and expressed the opinion that it changed into an anticline farther to the northeast, near Red Oak and Stennett; Keyes, in 1916, mentions its pres-

¹ Manuscript received by the Secretary of the Society January 23, 1922.

Published with the approval of the Director of the Iowa Geological Survey.

² J. E. Todd: On the folding of the Carboniferous strata in southwestern Iowa. Proceedings of the Iowa Academy of Science, vol. i, part i, 1889, p. 61; Some varied conclusions in Iowa geology, *ibid.*, vol. xiii, 1906, p. 184.

G. L. Smith: Carboniferous section of southwestern Iowa. Iowa Geological Survey, vol. xix, 1909, p. 612.

C. R. Keyes: Controlling fault systems of Iowa. Proceedings of the Iowa Academy of Science, vol. xxiii, 1916, p. 103.

John L. Tilton: The Thurman-Wilson fault through southwestern Iowa, and its bearing. The Journal of Geology, vol. xxvii, 1919, p. 383; Geology of Cass County. Iowa Geological Survey, vol. xxvii, 1916, published in 1920-1921, p. 211; Geology of Adair County, *ibid.*, p. 301; Carboniferous strata of the Missouri stage in southwestern Iowa, manuscript not yet published, Iowa Geological Survey.

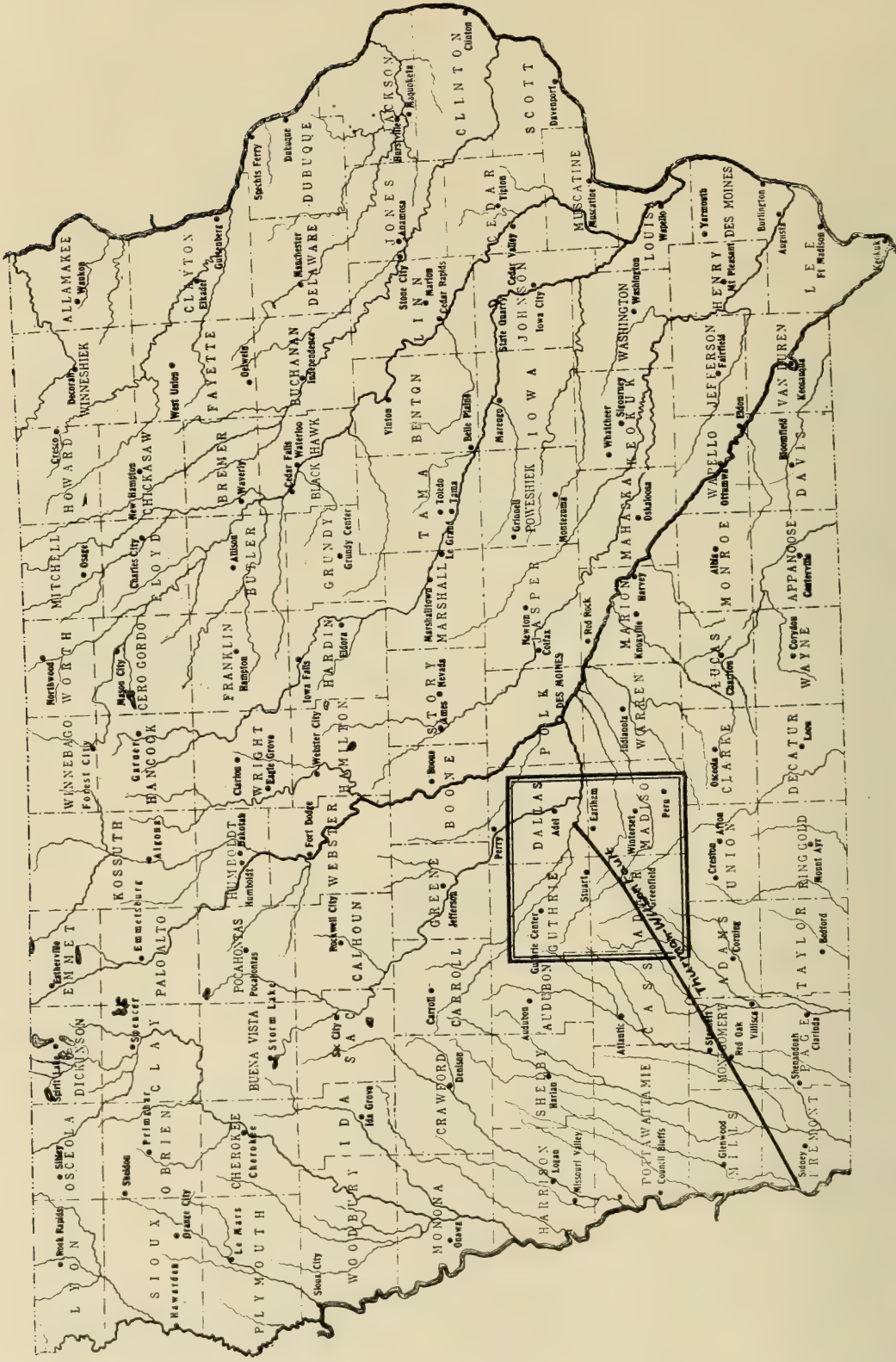


FIGURE 1.—Location of the Area near Stuart, Iowa

This area is in the west-central part of the State and, so far as traced, at the northeast end of the Thurman-Wilson fault.

ence near Red Oak without contributing any data with reference to it; Tilton came across it in 1915, north of Briscoe, north of Bridgewater, and farther to the northeast, in work in Cass and Adair counties, first published in 1919; described it as a normal fault downthrow on south side of 284 feet, and this last summer, 1921, located the fault definitely at three additional points:³ close to the river northwest of Red Oak, at the southwest corner of section 18, Harrison Township, Adair County, and close to the Dallas County line immediately northwest of Earlham. It is the effect of this fault and of erosion along it near Earlham and Stuart that is treated in this paper.

The area here considered is a critical one, bearing primarily on the relation of the Des Moines and Missouri stages in Iowa. The problem is not only of interest in Iowa, but also of interest as related to problems in that historic region of southeastern Nebraska, which area also lies on the upthrow side of the general direction of the Thurman-Wilson fault; and is of interest to oil men farther south, in Missouri, Kansas, and Oklahoma, who may wish to know of conditions affecting the boundary of these stages to the north.

AREA NEAR EARLHAM AND SOUTH OF FAULT

South and southeast of Earlham are extensive quarries, long known and visited by many geologists. Between the bed of North River, near by, and the top of the quarries may be seen all of the strata from the Hertha limestone to the top of the Winterset limestone. These same beds may be seen outcropping along North River to a point 2 miles southwest of Earlham. They may also be seen outcropping along ravines for about 3½ miles northeast of Earlham, to the border of the Missouri stage as it has long been mapped. A mile and a half north of Earlham there is a place on the hillside where a reddish sandy shale at the top of the Pleasanton appears beneath the Hertha limestone (the northwest quarter of the northwest quarter of section 31, in township 78 north, range 29 west).

AREA NEAR EARLHAM AND NORTHWEST OF FAULT

A mile and a half west-southwest of this last-mentioned point is a location in section 35 where 8 feet of a thin-bedded limestone overlies 8 feet of a gray, densely bedded limestone containing *Reticularia perplexa*, a surprisingly large number of *Spirifer cameratus*, numerous *Composita*

³ A report on the "Carboniferous strata of the Missouri stage in southwestern Iowa," by the writer, is now in the hands of the Iowa Geological Survey. It includes further discussion of the effects of the fault, the areal distribution of the subdivisions of the Missouri stage, and of the Des Moines stage in the area considered.

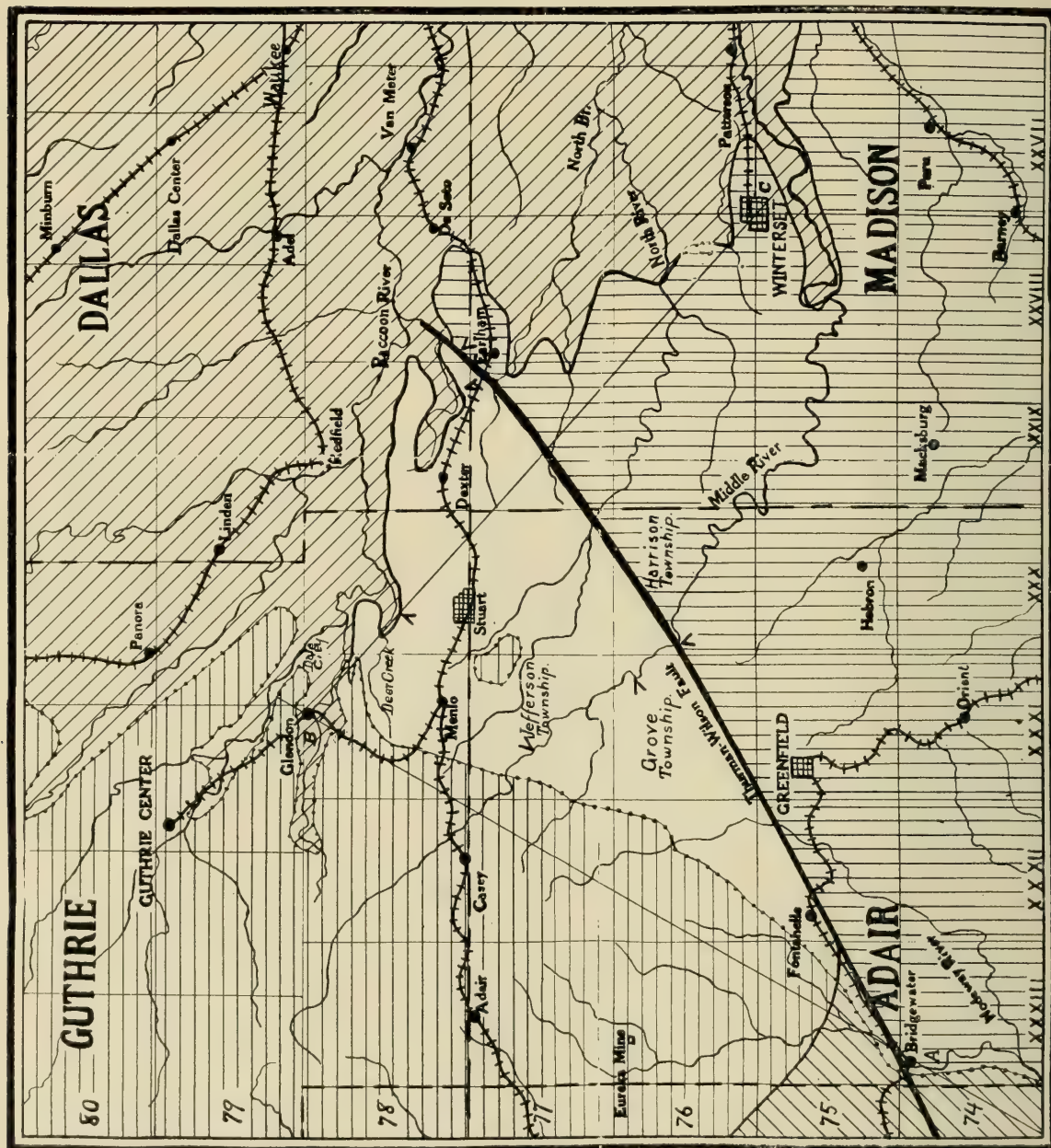
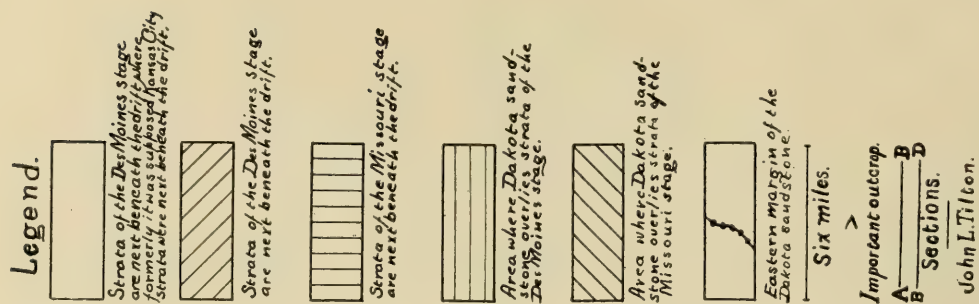


FIGURE 2.—Map of the Area near Stuart, Iowa

subtilita, many crinoid stems, and a few *Marginifera muricata*. Beneath these heavy beds about 3 feet of a gray shale appear exposed in the side of the trench. Two miles to the northwest of this outcrop are two outcrops of a very fragmental limestone in which no fossils were noted. In the judgment of the writer, these various beds in section 35 and to the northwest are not Hertha and other beds of the Kansas City division of the Missouri stage, as they have previously been mapped. They will be considered later as a portion of the Henrietta (Appanoose) substage of the Des Moines stage.

CONTRASTS ON THE TWO SIDES OF FAULT

The Hertha limestone universally in Iowa and northern Missouri has numerous *Composita subtilita* in it and occasionally representatives of other forms, but essentially only *Composita subtilita*. The topmost stratum of the Hertha on the south side of the fault-plane is dense and resistant to weathering. The previously supposed Hertha northwest of the fault contains few fossils, is arenaceous, and yields readily to weathering, so that the outcrops present a loose mass of arenaceous lumps. It is not Hertha limestone.

In the Ladore shale, just above the true Hertha limestone, on the south side of the fault, there is a bed of blue limestone that has coal below it and black shale above it. At the outcrop northwest of Earlham, beyond the fault, the shale that appears is an ordinary gray shale, with no evidence of blue limestone in the bed of the ravine nor along the side of the trench.

The true Bethany Falls (Earlham) limestone, next above the Ladore shale on the south side of the fault, has at its base a bed of limestone about a foot and a half thick. Above this base are beds of various thicknesses of limestone up to 6 inches, as may be seen in the old quarries east of Earlham and elsewhere. The beds of limestone across the fault to the northwest of Earlham are divided into two parts. The basal portion, 8 feet thick, is a continuous mass of limestone. The upper portion is scarcely more than calcareous shale. Further, the assemblage of fossils found in the lower portion, even without the *Marginifera muricata*, which is considered an index fossil of the Des Moines stage, is such as can not be found anywhere in the Bethany Falls (Earlham) limestone of Iowa. The assemblage is marked by exceedingly numerous *Reticularia perplexa*, with frequent *Spirifer cameratus*, *Composita subtilita* and crinoid stems, and the presence of *Marginifera muricata*. Such a succession of strata and assemblage of fossils are not to be duplicated either in the Pleasanton

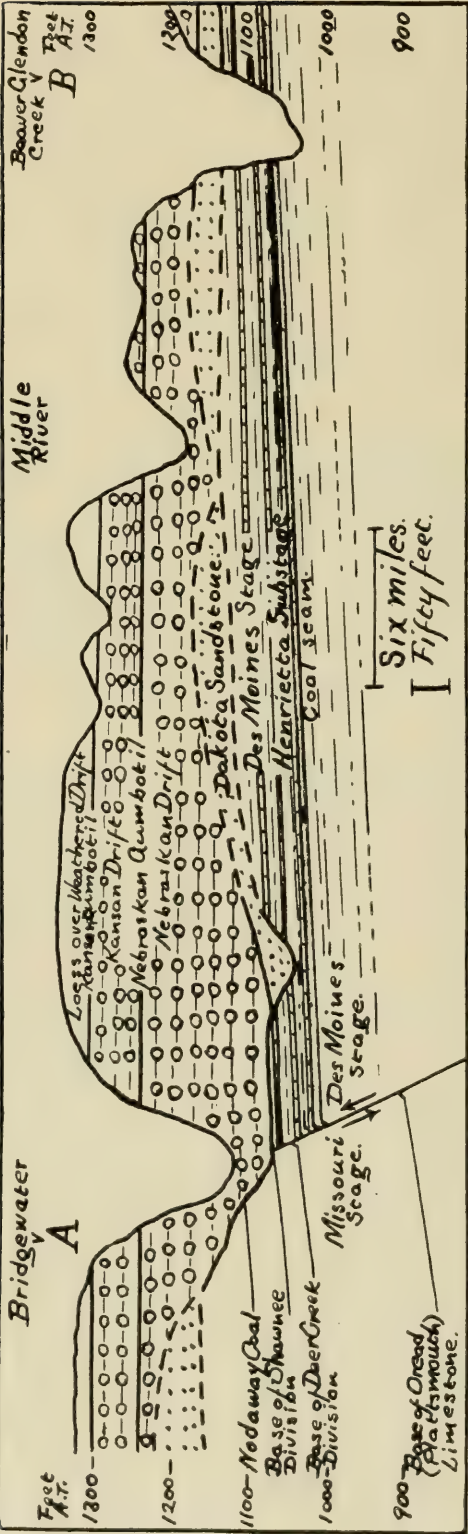


FIGURE 3.—Section from Bridgewater to Glendon, A—B on the Map of the Area

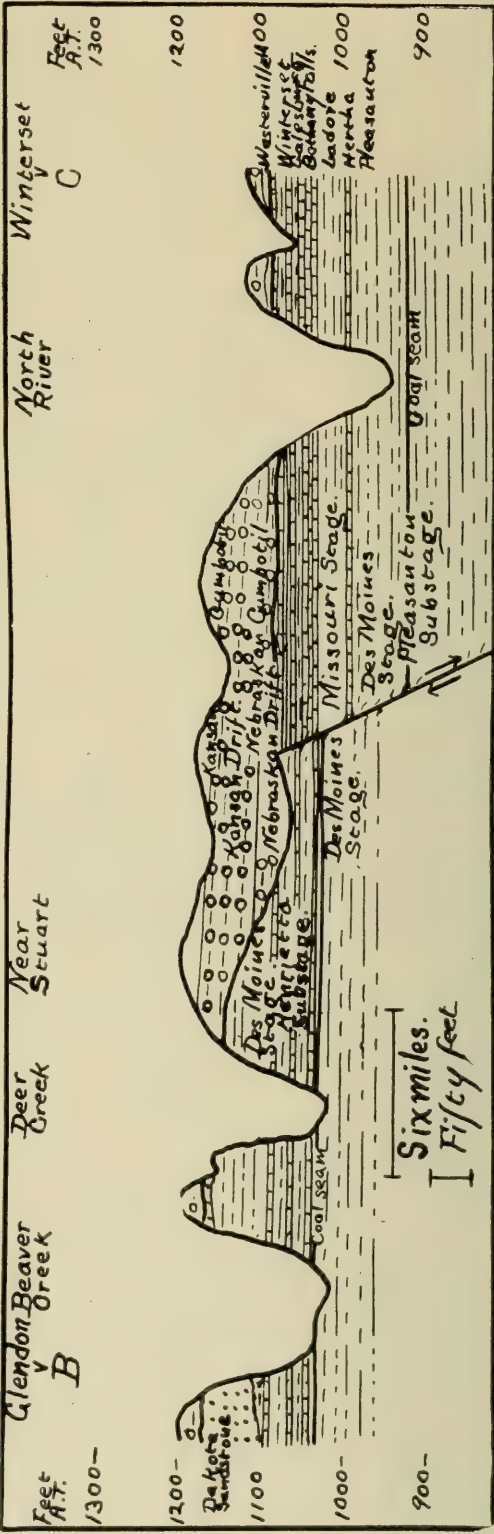


FIGURE 4.—Section from Glendon to Winterset, B—C on the Map of the Area

shale immediately across the fault to the east nor in the outcrops along Middle River farther south.

There is the further positive argument (to be presented later) that the set of beds described north of the fault fits into the Henrietta (Appanoose) substage as seen north of Centerville, Iowa.

The fault-plane, then, extends between the outcrop of true Hertha limestone with the Pleasanton shale beneath it, as seen directly north of Earlham, and the outcrop a mile and a half west-southwest from that outcrop.

AREA NORTH OF STUART, ALONG DEER CREEK, NORTH OF FAULT

Farther west, north of Stuart, these same beds north of the fault appear along a creek known as Deer Creek. The following section may be found extending from the brow of the hill south of Deer Creek down to the bed of that stream, along the main road north from Stuart, only 2 miles from that town. A considerable portion of the section is duplicated along Rocky Run, a mile to the east, on the opposite side of the same hill:

Section along Road in Penn Township, Guthrie County, east of the northeast Quarter of Section 20, two Miles north of Stuart

	Feet.	Inches.
7. Limestone, gray, in loose weathered fragments; crinoid stems and many shell fragments.....	4-5	..
6. Shale, clayey, red.....	8	..
5. Limestone, gray; three main divisions with shaly partings, lowest division nodular; <i>Cosposita subtilita</i> , corals, and many shell fragments.....	5	..
4. Shale, gray, calcareous in places.....	4	..
3. Sandstone, brown, shaly (ripple-marks at Rocky Run).....	1	3
2. Shale, clayey, light gray.....	15	..
1. Limestone, brownish, arenaceous; fragmental part of arenaceous balls; <i>Composita subtilita</i> , apparently <i>Marginifera muricata</i> ; few fossils at this point.....	3	10
Bed of Deer Creek.		
Total.....	42	1

Following Deer Creek down from the base of the above section the strata are continued. One comes on 20 feet of shale beneath the limestone (number 1); then a foot and a half of blue limestone containing *Composita subtilita*, *Marginifera muricata* (an index fossil of the Des Moines stage), *Productus cora*, gasteropods, and numerous pelecypods. Then come 6 feet of a black shale, with 10 inches of coal beneath it. (It is this

seam of coal specially designated in the cross-sections that is mined to the west, along Deer Creek, and formerly at Eureka mine, to the southwest.) Next come 14 inches of a brownish micaceous sandstone above 6 feet of arenaceous shale; then 3 feet of a dark arenaceous limestone lying 10 feet above the river bed at that point.

Interest centers in the 3 feet 10 inches of limestone (number 1 of the above section), Bain's "fragmental limestone." Below this bed of limestone the strata are distinctly Des Moines in character, and were so considered by Bain when he mapped Guthrie County. The bed of fragmental limestone (number 1) was, however, considered the base of the Missouri stage, and the limestone beds up the hill (which are thicker as exposed farther west) were considered Bethany Falls⁴ (Earlham) and Winterset beds respectively. The beds can be traced through sections 7, 8, 9, 17, 18 (range 30), and sections 12 and 17 (range 31) north of the creek, and sections 21, 20, 19 (range 30), and section 14 (range 31) south of the creek.

A detailed comparison between the beds of limestone (number 1) that is fragmental in character (previously supposed Hertha) and the true Hertha east and south of Earlham—and elsewhere south, even into Missouri—reveals marked differences: This Guthrie County limestone north of Stuart is in one continuous bed, while the real Hertha elsewhere is in two portions, with a bed of shale between them. Furthermore, this Guthrie County bed of limestone is of a very different texture than the Hertha. It is brownish and arenaceous, the fragments not composed of calcareous ball and rod-like lumps found in the Hertha. They are arenaceous. Along with *Composita subtilita* the present writer found an imperfect shell that he judged to be *Marginifera muricata*, the index fossil of the Des Moines stage. The fauna listed on page 448 of the Guthrie County report⁵ is not found in the Hertha limestone of Iowa as characteristic of it, even though a tabular list of fossils of all kinds found over large areas may include them all.

The brownish weathered sandstone about 15 inches thick (number 3) is not in the least like the foot and 10 inches of dark blue limestone found at Winterset, in the upper portion of the Ladore shale, above the Hertha limestone, with which it should agree if Bain's correlation were correct.

The next limestone (number 5), which is 5 feet thick and located above 4 feet of shale, has a character in a general way like that of the Bethany Falls (Earlham) limestone, but the lower beds lack the thick-

⁴ John L. Tilton: The proper use of the geological name "Bethany." Proceedings of the Iowa Academy of Science, 1913.

⁵ Iowa Geological Survey, vol. vii, p. 448.

ness found at the Earlham quarries and lie beneath 8 feet of red shale unlike that reported elsewhere.

The limestone above the red shale (number 7), the uppermost of the three limestone beds north of Stuart, contains many shell fragments and some crinoid stems, but it is unlike either the Winterset or the so-called De Kalb (really Westerville) limestone; especially is it unlike the latter in the number of *Fusulina*, with which it seems to have been correlated instead of with the Winterset, for it is that bed and not the Winterset that contains the *Fusulinas*. Thus this stratum⁶ (number 7) does not fit into the Winterset section.

From the above comparisons it is evident that the limestone beds in the hills along Deer Creek north of Stuart do not belong to the Kansas City division of the Missouri stage. They do, however, agree in character and in fossil content with the beds northwest of Earlham and they follow without break the beds farther north of Stuart, at Dale City and Glendon.

AREA SOUTHWEST OF STUART, ALONG MIDDLE RIVER, NORTH SIDE OF FAULT TO FAULT-LINE

Looking southwest from Stuart, one comes upon limestone that Middle River reaches in section 16, Jefferson township, Adair County, at a point 6 miles west and 3 south from Stuart. The river crosses the level of the bottom of this limestone within a mile, but the thickness in the ravines bordering the valley on the west increases to $17\frac{1}{2}$ feet 5 miles down the river, where limestone was formerly quarried. Here likewise the abundance of *Reticularia perplexa*, associated with *Composita subtilita* and *Spirifer cameratus*, in a thick bed beneath a thin shaly upper portion, reproduces the conditions found northwest of Earlham. To further emphasize the relation, a recent boring for coal near Howell's store reached an 18-inch seam of coal at a depth of 95 feet below the side of the ravine. This is the seam found outcropping along Deer Creek north of Stuart, mined northwest of Stuart, and formerly at Eureka mine, in western Adair County, but not found near the surface east of the fault.

A mile farther south there is a slight exposure of the same limestone in the center of section 13, Grove township. A mile straight east from this point is another exposure of limestone, on the south side of the river, in the northeast quarter of the southeast quarter of section 18, Harrison township. Here, at a lower level than at the limestone a mile west, one comes on beds far above the others stratigraphically, for the grouping of beds and the presence of the dark chert with *Fusulina* are characteristic

⁶ This stratum is Bain's number 5, as given on page 448 of the *Geology of Guthrie County*. Iowa Geological Survey, vol. vii.

of the Deer Creek⁷ beds north of Stennett, but the Meadow and other beds belonging above them stratigraphically are here removed by erosion.

POSITION OF THE FAULT

The Thurman-Wilson fault, which had previously been located northwest of Red Oak, northwest of Briscoe, and near Bridgewater, thus lies between the center of section 13, Grove township, and the northeast quarter of the southeast quarter of section 18, Harrison township; and the extension of it toward the northeast passes north of Earlham, between the outcrop in the northwest quarter of the northwest quarter of section 31 (township 78 north, range 29 west) and the outcrop a mile and a half west-southwest from that location. It should be noted that at both of the locations of the fault in the area here considered the lines that cross the fault run diagonally to it, so that the location of the fault is limited to a much shorter distance, if measured in a direction at right angles to the direction of the fault. As worked out in a previous report,⁸ the fault is a normal fault, with fault-plane dipping steeply to the southeast. In the southwestern part of the State the locations made a straight line, but in the region here considered there is a marked curve to the north.

STRATIGRAPHIC POSITION OF BEDS ON THE UPTHROW SIDE OF FAULT

What are the beds that lie on the west (upthrow) side of the fault from section 18, Harrison township, to north of Earlham?

Bain,⁹ in his report on Guthrie County beyond the supposed base of the Missouri stage near Stuart, remarks on the "great similarity" of the apparently upheaved beds found farther north "to those in the upper portion of the Cherokee shales," but did not include in the comparison the strata immediately north of Stuart.

Leonard,¹⁰ in his report on Dallas County, mentions both *Chonetes mesolobus* and *Marginifera (Productus) muricata* as found near Adel, which is in the Des Moines stage and on the upthrow side of the fault. *Chonetes mesolobus* is also reported from strata well down in the Des Moines stage in Polk¹¹ and Keokuk¹¹ counties. It is reported from the

⁷ Deer Creek is here used in its geological sense, as the name of a portion of the Shawnee division of the Missouri stage. Deer Creek, as previously used in this paper, happens to be the name of a small stream north of Stuart and is without geological significance.

⁸ John L. Tilton: *Geology of Cass County*, p. 211, and *Geology of Adair County*, p. 302, both reports in the *Iowa Geological Survey*, vol. xxvii.

⁹ H. Foster Bain: *Geology of Guthrie County*. *Iowa Geological Survey*, vol. vii, 1896, pp. 429 and 445.

¹⁰ A. G. Leonard: *Geology of Dallas County*. *Iowa Geological Survey*, vol. viii, 1897, p. 71.

¹¹ *Iowa Geological Survey*, vol. vii, p. 331, and vol. iv, p. 272.

southern faunal area of the Pleasanton substage of Missouri.¹² In Iowa it is at least not a common fossil in the upper part of the Pleasanton substage near the base of the Hertha limestone, for up to the present there is no record of its existence there in the other counties just east of Missouri stage strata. *Marginifera muricata* is found throughout the Des Moines stage and is especially common in the lower part of the Pleasanton substage, where it forms bands of limestone in the shale. The presence of these two fossils in the strata close to Adel therefore favors the judgment that the strata at Adel belong well down in the Des Moines stage rather than close to the base of the Hertha limestone, as originally supposed.¹³

¹² Hinds and Greene: The stratigraphy of the Pennsylvanian series in Missouri, table, p. 276. Compare also statements on pages 267, 268, 270, and table, p. 274.

¹³ Formerly it was thought in Iowa that *Marginifera (Productus) longispina* was as truly an index fossil of the Missouri stage as *M. muricata* is of the Des Moines stage, but literature with reference to *M. longispina* (and also of *M. wabashensis*, a possible synonym) does not support that view.

Stuart Weller, in Bulletin 153, U. S. Geological Survey, lists *Productus muricatus*, *P. longispinus*, and *P. wabashensis* as three distinct species and *P. splendens* as a synonym of *P. longispinus*.

George H. Girty in his Paleontology of the Pennsylvanian of Missouri (Hinds and Greene, Stratigraphy of the Pennsylvanian series of Missouri, 1915, table, p. 303, and text) lists *M. wabashensis* as found in Cherokee shales of the Des Moines stage, ? in the Henrietta, and present in all divisions of the Missouri stage excepting the Wabaunsee. He also mentions *M. muricata (Chonetes mesolobus*, etc.) as restricted to the Des Moines group (stage). Idem, 281.

In Iowa H. G. Leonard lists *P. longispinus* as found with *P. muricatus* and *Chonetes mesolobus* close to Adel. H. Foster Bain names it as found in the limestone north of Stuart, and Samuel Calvin as found near Logan, in Harrison County. In the last two places it was at the time supposed that the strata were in the Missouri stage. In all three places it is now found that the strata are in the lower part of the Des Moines stage.

G. L. Smith, in his earliest paper on The paleontology and stratigraphy of the Upper Carboniferous of Iowa (Proceedings of the Iowa Academy of Science, vol. xxii, 1915), names *P. muricatus* and *P. longispinus* as both found in the City Bluff shale. In a later paper (idem, vol. xxv, 1918, p. 535) he comments on criticism for identification of *M. muricata* in the Forbes (Deer Creek) and City Bluff shale, and in the table that follows lists *M. wabashensis* as a synonym for *M. longispina*. In his contributions published in 1916 (idem, vol. xxiii, p. 87) he had mentioned *M. longispina* as found near the Nyman coal and *M. wabashensis* as found near Thurman. The locations at Thurman, at the Nyman coal, and at the City Bluff beds are all in the Wabaunsee of the Missouri stage, the division from which in Missouri Girty did not report that species.

F. B. Meek considered both *P. splendens* and *P. wabashensis* as synonyms of *P. longispinus*. Final Report of the U. S. Geological Survey of Nebraska, etc., 1872, p. 162.

C. A. White thought both *P. muricatus* and *P. longispinus* ranged "through the whole of the Carboniferous or Coal Measure series." U. S. Geological Survey West of the 100th Meridian, vol. iv, 1877, pp. 119 and 120.

G. H. Girty, in his report on The stratigraphy and paleontology of the Upper Carboniferous Rocks of the Kansas Section, Bulletin 211 of the U. S. Geological Survey, 1903, lists *M. muricata* as found not only in Cherokee, Fort Scott, Labette, and Parsons members of the Des Moines stage, but also in the Deer Creek and Le Compton of the Missouri stage. *M. wabashensis* he reports from twelve different horizons—two in the Des Moines stage, nine in the Missouri stage, and one in the Permian.

The present writer, having noted the evidence of a fault through the region and knowing that the strata found did not reproduce any part of the upper portion of the Des Moines stage,¹⁴ visited the region north of Centerville and near Rathbun¹⁵ and there noted the same general relation of strata found northwest of Earlham and north of Stuart and the same assemblage and relative abundance of fossils in the upper portion of a 4½-foot bed of dense limestone. The entire section as found had at the top a bed of red shale with iron concretions in it, above a bed of limestone 8 or 10 inches thick. Beneath this was a 12-foot bed of shale, chiefly gray, including a 6-inch bed of decomposing limestone. Next, at the base, came a 3-foot bed of fragmental, siliceous limestone, above 4½ feet of limestone the upper half of which was very fossiliferous, the list including *Hustedia mormoni*, *Composita subtilita*, many *Reticularia perplexa*, *Spirifer cameratus*, large *Fusulina cylindrica*, *Naticopsis*, *Euomphalus*, a pelecypod, *Phillipsia major*, and crinoid stems; no *Marginifera muricata* were noted. This larger assemblage of fossils than found near Earlham and Stuart may be due to the longer time spent in the search, though the time was limited. The relative abundance of *Reticularia perplexa* was certainly striking, even though that fossil does have a long range. These beds are 80 miles from Stuart, but they are in the direction of strike of the region and are the only beds that show a marked similarity to those near Stuart. The similarity is such that the writer believes the beds north of Stuart and northwest of Earlham should be correlated as Henrietta (Appanoose) beds. The amount of throw along the Thurman-Wilson fault, as determined by Smith,¹⁶ near Thurman, is 300 feet; as determined by Tilton,¹⁷ for southeastern Cass County, it is 284 feet, a displacement that is about right to bring beds near the base of the Des Moines stage near the surface. At Van Meter, a few miles east of Earlham, and on the downthrow side of the fault, Leonard¹⁸ mentions a mine 300 feet deep which he judges stops 100 feet above the base of the Des Moines stage.

The anticline that Leonard notes in Dallas County and calls the Red-field anticline¹⁹ has the same relation to the fault that the gentle anticline

¹⁴ John L. Tilton: Geological section along Middle River, in Central Iowa. Iowa Geological Survey, vol. iii, p. 135; Geology of Warren County, idem, vol. v; Geology of Madison County, idem, vol. vii; Geology of Clarke County, idem, vol. xxvii.

¹⁵ H. Foster Bain: Geology of Appanoose County. Iowa Geological Survey, vol. v, 1895, p. 378. Unfortunately there is no list of fossils given.

¹⁶ George L. Smith: Carboniferous section of southwestern Iowa. Iowa Geological Survey, vol. xix, p. 612.

¹⁷ John L. Tilton: Geology of Cass County. Iowa Geological Survey, vol. xxvii, p. 211.

¹⁸ A. G. Leonard: Geology of Dallas County. Iowa Geological Survey, vol. viii, 1897, pp. 92-94.

¹⁹ Idem, p. 91.

has near Lewis, in Cass County, which parallels the west side of the fault on the upthrow side.

BEARING OF FAULT ON POSITION OF COAL AND ON LAY OF STRATA TO THE NORTH

No one has yet traced the fault-plane farther to the northeast than the region described in this paper, but the fault evidently has an important economic bearing on the position and relation of coal north of the fault, as near Panora, Perry, and Boone, to that south of the fault, as at Van Meter, Des Moines, Orolabor, and Enterprise.

To the northeast, along the general direction of the fault, there are peculiarities in the distribution of the Mississippian, Upper Devonian, and Silurian strata, most of which have been classed as evident discontinuities, but the direction of the fault is certainly suggestive of the possible presence of another factor. It can not at present be affirmed whether or not the fault, or a series of parallel faults, extends into that area, or whether or not the disturbance there becomes a fold.

BEARING OF FAULT ON POSITION OF COAL WEST OF STUART

The relations along the fault make it evident that for some distance west of Stuart there is an area beneath the drift and the Dakota sandstone that may be expected to bear coal, the amount and extent of which coal can only be ascertained by prospecting. Previously it was thought that the coal mined at the old Eureka mine, in western Adair County, came from a small seam 30 feet below the Hertha limestone; but we must now recognize that that seam is one of those deep down in the Des Moines stage, related to those below the Appanoose beds in the southeastern part of the State.

EFFECT ON THE INTERPRETATION OF DEEP WELL RECORDS, AND GEOLOGICAL MAP OF IOWA

Up to the present time the apparent absence of distinct Kansas City strata in the deep well at Atlantic²⁰ has seemed strange. Now the significance of the apparent absence is clear. There are no Kansas City beds in that part of the State.²¹ At Stuart there is a deep well, to the correct

²⁰ W. H. Norton: Underground water resources of Iowa. Iowa Geological Survey, vol. xxi, p. 1121.

John L. Tilton: Geology of Cass County. Idem, vol. xxvii, p. 257.

²¹ This statement is in part dependent on evidence that the Kansas City stage is lacking farther west in Iowa—a point discussed in a paper on The Carboniferous strata of the Missouri Stage in Southwestern Iowa, accompanied by sections and a map of the surface distribution of the subdivisions of the Missouri stage, by the present writer. This paper is now in the possession of the Iowa Geological Survey.

interpretation of which the facts presented in this paper are necessary. Finally, the recognition of the strata to the north, to the west, and to the southwest of Stuart as of the Des Moines stage instead of the Missouri stage necessitates a pronounced change in the geological map of Iowa for this region.²²

²² See accompanying map and sections. The outline of the eastern margin of the Dakota sandstone is as given in the reports on the geology of Guthrie and Adair counties in the Iowa Geological Survey, vol. vii and xvii, and the exact position of the fault here given from data secured in the summer of 1921 corrects the location of the fault as given in the map of Adair County (*idem*, vol. xxvii). When the map of Adair County was prepared the outcrops in Jefferson and Grove townships were supposed to be of strata in the Missouri stage. It is now found that they are in the Des Moines stage (Henrietta).

FRONT RANGES OF THE ANDES BETWEEN SANTA CRUZ,
BOLIVIA, AND EMBARCACION, ARGENTINA ¹

BY KIRTLEY F. MATHER

(Presented before the Society December 28, 1921)

CONTENTS

	Page
Introduction.....	704
Bibliography.....	706
Physical geography.....	707
General.....	707
Mountain ranges.....	707
Sierra de Santa Cruz.....	707
Sierra de Florida.....	707
Sierra de Limon.....	709
Sierra de Charagua.....	711
Sierra de Mandiyuti.....	715
Sierra de Guarui.....	717
Sierra de Aguarague.....	717
Sierra de Vitiacua.....	719
The Chaco.....	721
Intermontane lowlands.....	723
Drainage system.....	725
Physiographic history.....	726
Stratigraphy.....	729
General statement.....	729
Espejos formation.....	730
Los Monos shale.....	731
Bermejo series.....	733
Origin of the name and limit of the series.....	733
Oquita formation.....	734
Mandiyuti conglomerate.....	736
Machareti formation.....	739
•Vitiacua limestone and chert.....	739
Tacuru formation.....	741
Tatarenda formation.....	746
Quaternary deposits.....	750
Geologic structure.....	750
General statement.....	750
Florida fault.....	753

¹ Manuscript received by the Secretary of the Society May 26, 1922.

	Page
Limon fault and anticline.....	753
Charagua anticline.....	754
Oquita-Taimbermi fault.....	755
Mandiyuti fault and anticline.....	757
Guarui fault.....	758
Chireti fault.....	758
Vitiacua fault and anticline.....	758
Aguarague fault and anticline.....	759
Geologic history.....	761
Devonian Period.....	761
Permo-Carboniferous and Permo-Triassic time.....	762
Late Mesozoic time.....	762
Tertiary Period.....	763
Quaternary Period.....	763

INTRODUCTION

The following notes concerning the general geology of the Front Ranges of the Andes between 18 degrees and 23 degrees south latitude were obtained during a rapid reconnaissance made in January and February, 1920. They are published through the courtesy of Richmond Levering and Company, for whom the geological examinations were made. Very few geological data are available concerning this little-known region, so that it is hoped the material presented here will be of interest and value in spite of the many obvious deficiencies, which in part resulted from the rapidity with which the field observations had to be made.

S. C. Herold (1920)² has recently summarized the scattered literature pertaining to the southern half of the area under discussion. The data which he presents will not be recounted here, as his paper is accessible to all geologists. In March, 1922, while this manuscript was receiving its final revision before publication, my attention was directed by Mr. Chester Washburne to an important memoir which had just appeared from the pen of Dr. Guido Bonarelli (1921). This paper is easily the most important contribution yet made to a knowledge of the eastern Andes of northern Argentina and southern Bolivia. In it the author has gathered together résumés of all earlier reports which deal with the stratigraphy of that and adjacent regions. The most significant of the new data which he presents relate to the age of the so-called "Horizonte Calcereo-dolomitico," previously considered by most authors as belonging to the Cretaceous system. Dr. Bonarelli presents convincing evidence to prove that this formation is of late Triassic or early Jurassic age. References to

² References may be found in the accompanying bibliography.

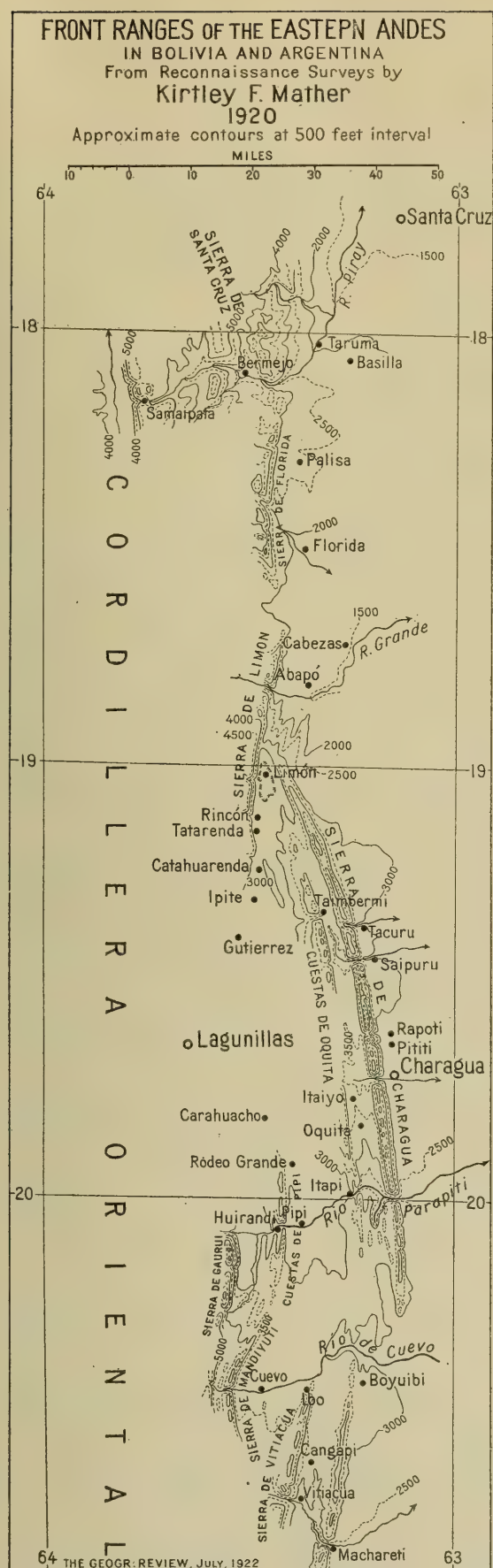


FIGURE 1.—Map of the Front Ranges of the Andes between Santa Cruz, Bolivia, and Embarcación, Argentina

This cut is furnished through the courtesy of the Geographical Review, published by the American Geographical Society, Broadway at 156th street, New York.

this paper will be made at appropriate places in the following paragraphs. Because of the information thus made known, certain slight changes will be noted in these pages if they are compared with the abstract of this paper prepared in November, 1921.

BIBLIOGRAPHY

- G. BODENBENDER: Inf. sobre una explor. geol. en la region de Oran. Bol. del Minist. de Agric., volume IV, numbers 4 and 5. Buenos Aires, 1906.
- G. BONARELLI: Las sierras suband. del Alto y Aguarague y los yacm. petr. del Dist. Min. de Tartagal. Anal. Minist. Agric., Sec. Geol., volume VIII, number 4. Buenos Aires, 1913.
- Explor. de la region petrolif. de Salta. Anal. de la Soc. Cient. Arg., volume LXXVI, number 1. Buenos Aires, 1913.
- La estruct. geol. y los yacm. petr. del Dist. Min. de Oran. Minist. Agric., Dir. Gen. de Min., Geol., etcetera, Bol. number 9, Serie B. Buenos Aires, 1914.
- Terc. cont. al Conoc. Geol. de las Regiones Petr. suband. del norte (Salta y Jujuy). Minist. Agric., Sec. Geol., volume XV, number 1. Buenos Aires, 1921.
- L. BRACKEBUSCH: Estudios sobre la formac. petrolif. de Jujuy and Viaje a la prov. de Jujuy. Acad. Nac. de Ciencias de Cordoba, Bol., Tome V, entr. 2a, pages 135-254. Buenos Aires, 1883.
- E. DE CARLES: Sobre algunos yacm. petrolif. en el Aguaray y Tartagal, provincia de Salta. Anal. Mus. Nac. de Hist. Nat., volume XXII, pages 257-266. Buenos Aires, 1911.
- Nuevas consid. sobre las form. petr. de Tartagal y Aguaray. Ditto, volume XXIV, December number. Buenos Aires, 1913.
- J. FELSCH: Informe preliminar sobre la region petrolif. en la Cord. Real de Bolivia entre Yacuiba y Santa Cruz. Los Petroleos de Bolivia, Cia. Caupolican y Calacoto, pages 65-79. Santiago, 1920.
- K. C. HEALD and K. F. MATHER: A reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia. Bulletin of the Geological Society of America, volume 33, pages ——. New York, 1922.
- S. C. HEROLD: The economic and geologic conditions pertaining to the occurrence of oil in the north Argentine-Bolivian field of South America. Transactions of the American Institute of Mining Engineers, volume 61, pages 544-562. New York, 1920.
- H. HOEK and G. STEINMANN: Erlaut. z. Routenkarte d. Exped. Steinmann, Hoek, v. Bistram in d. Anden v. Bolivien. Peterm. Mitt., volume LII, pages 1-20. Gotha, 1906.
- K. F. MATHER: The front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina. Abstract. Bulletin of the Geological Society of America, volume 33, pages 138-140. New York, 1922.
- Along the Andean front in southeastern Bolivia. Geographical Review, volume XII, pages 358-374. New York, 1922.
- H. S. PALMER: Geological notes on the Andes of northwestern Argentina. American Journal of Science, volume 38, pages 309-330. New Haven, 1914.

W. SCHILLER: Contrib. al conoc. de la form. petrolif. (Cretáceo) de Bolivia del Sud. Revista del Mus. de la Plata, volume XX, pages 168-197. Buenos Aires, 1913.

G. STEINMANN, H. HOEK, and A. VON BISTRAM: Zur Geologie des sudostrichen Boliviens. Centralblatt für Min., Geol., und Pal. Stuttgart, 1904.

PHYSICAL GEOGRAPHY

GENERAL

The territory between 63 degrees and 64 degrees west longitude and 18 degrees and 23 degrees south latitude is occupied by the most easterly ranges of the Cordillera Oriental, or eastern Andes, the foothills bordering these ranges, the intermontane lowlands which separate them one from the other, and the west margin of the broad interior plains known as the Gran Chaco (see map, figure 1). In general the territory west of 63° 30' lies in the Cordilleran physiographic province, while that to the east of this meridian is a part of the Interior Lowlands, but the boundary line between the two provinces is by no means straight; rather, its position is shifted in different parts of the area studied, from near the sixty-third meridian nearly or quite to the sixty-fourth.

MOUNTAIN RANGES

Sierra de Santa Cruz.—The Sierra de Santa Cruz is the front range of the Andes from the eighteenth parallel northward to the latitude of Santa Cruz and beyond for an unknown distance to the northwest, forming a great arc very convex toward the southwest.⁴ The rugged heights of this sierra rise to elevations of five or six thousand feet above the sea and are separated by numerous steep-walled canyons, deep carved into resistant sandstones. Its eastern margin is marked by *cuestas*, inclined eastward at angles of 20 degrees to 40 degrees, composed of massive red beds which dip beneath the sands and clays of the adjacent plain.

Sierra de Florida.—The Sierra de Florida continues the Andean system southward from 18° 10' to 18° 35'. Its eastern front is a sheer cliff extending in a general north-south direction for a distance of about 22 miles and broken by stream channels only at long intervals. Rugged and forbidding peaks crowd close on each other throughout the region west of this bold escarpment and presumably merge at the western margin of the range into the next mountain group of the Cordillera Oriental. The range itself was not entered; the observations on its geology were made from the trail which leads southward through Palissa and Florida, paralleling the mountain front at a distance of 4 or 5 miles.

⁴ K. C. Heald and K. F. Mather, 1922.

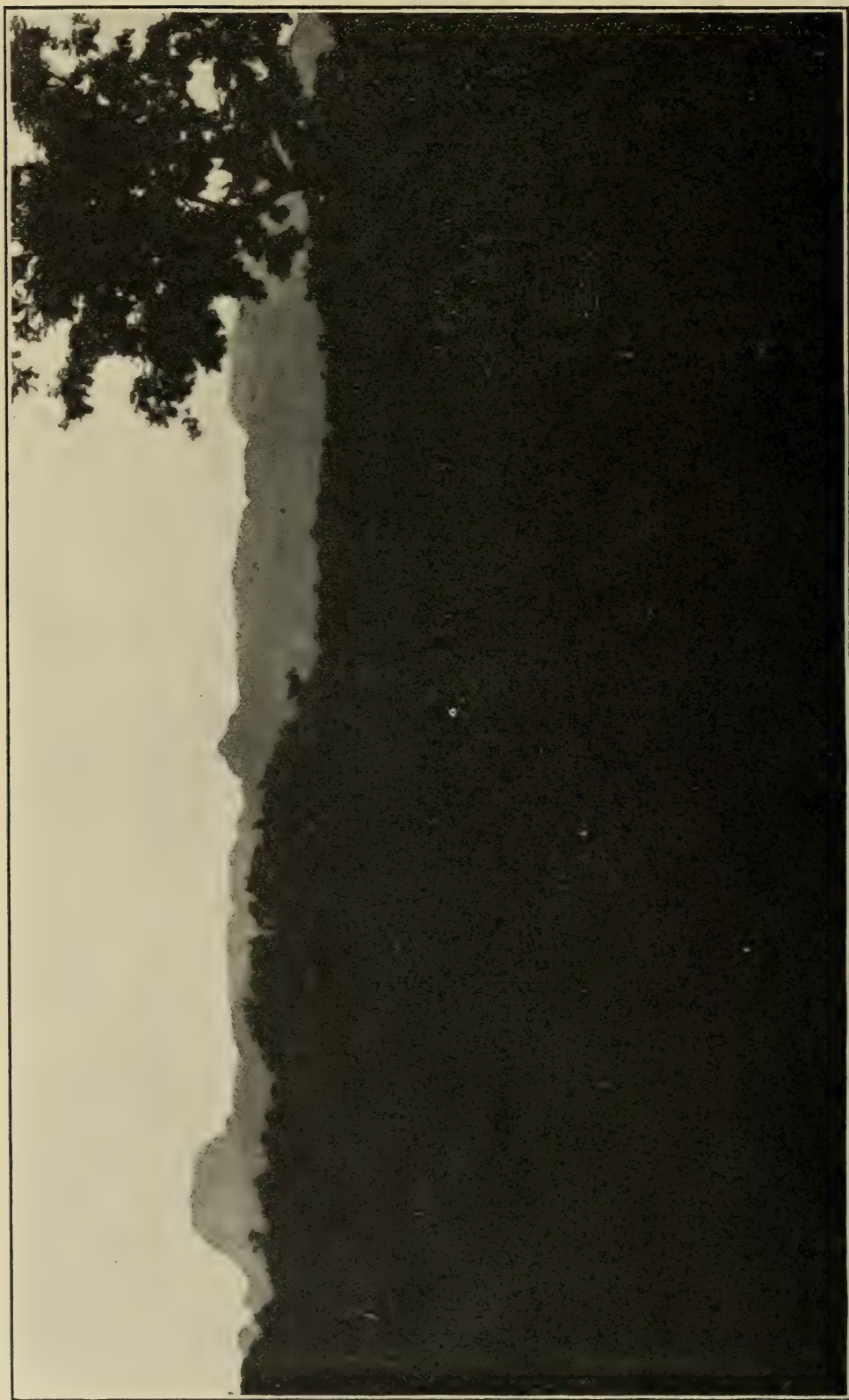


FIGURE 2.—*The Sierra de Florida*

The view is taken from the sand hills near Palissa. At the left is Mount Cuchilla, and among the clouds beyond the tree at the right is Mount Carobana.

The two most prominent peaks in this mountain group are Mount Carobana and Mount Cuchilla. The former is a broad dome-shaped elevation with slopes which rise precipitously to a rounded crest, several hundred feet higher than the neighboring summits. Mount Cuchilla is 9 miles farther south, and, as the name implies, is a knife-edge ridge trending northeastward. Its slopes are carved into shelf-like flats and pitches due to the uneven resistance of the nearly horizontal strata of which it is composed. The sky-line formed by it may be seen in the photograph, figure 2. Between these two peaks the rugged sierra displays two deep indentations formed by youthful valleys which lead back into the interior of the range. The more northerly of these canyons is occupied by the upper portion of Rio Florida; the more southerly by a large tributary to that stream. The Florida flows southeast past the town of the same name, and then swings due eastward out on the plain, and is finally tributary to Rio Grande.

Sierra de Limon.—South of Mount Cuchilla the Sierra de Florida declines rapidly in elevation and in a short distance dwindles to a line of low hills. A few miles farther to the south, in latitude $18^{\circ} 40'$, the northern outposts of the next mountain range, the Sierra de Limon, appear. These are hogback hills inclined westward and increasing in altitude toward the south until they attain mountainous elevations 4 or 5 miles north of the Rio Grande Valley. That portion of the Sierra de Limon which lies north of the nineteenth parallel is the front range of the Andes system and overlooks the interior plain which stretches eastward from its foot. Six to 8 miles east of the Sierra de Limon, approximately on the nineteenth parallel, there are the northern hills of the Sierra de Charagua. This sierra is the front range throughout its entire length, and its northern portion thus overlaps the southern half of the Sierra de Limon, from which it is separated by the Limon Valley. The southern half of the Sierra de Limon overlooks this intermontane lowland and is the second range from the front of the Andes system.

Throughout its entire extent the Sierra de Limon is a mass of extremely rugged mountains characterized by narrow canyons and sheer precipices which rise to serrate summits. In general these display a close accordance in altitude, estimated at about 5,000 feet above sealevel, and approximately 2,000 feet above the lowland on the east. Toward the north the summit elevations decline regularly until the mountains become low hills due west from Cabezas. The southern termination of the range has not been observed.

In the vicinity of the Rio Grande the east front of the Sierra de Limon is an almost unbroken fault-scarp rising sheer above the plain. Rio



FIGURE 3.—*East Side of the Sierra de Charagua*

View is taken south of Saipuru. Resistant Tacuru sandstones rising from beneath the plains of the Bolivian Chaco form hogbacks along the flank of the Charagua anticline.

Grande flows eastward from the midst of the rugged mountains beyond this scarp, through which it has cut a broad deep notch, the only breach in the mountain barrier throughout its entire length. Between 5 and 15 miles south of the Rio Grande the Limon range is fronted by a series of foothills which appear to form the junction between it and the north end of the Sierra de Charagua. The trail through these hills winds along the bottom of wooded quebradas, so that it was not possible to obtain a good view of that portion of the mountains. South of the saddle through which the trail enters the Limon Valley, 4 miles north of Limon, the steep eastern front of the Limon range presents a rather unusual topography. Half way up the 1,500-foot scarp there projects a series of bench-like secondary ridges which trend at right angles to the axis of the main ridge. These are all very short, are separated from each other by steep, narrow, V-shaped ravines, and terminate abruptly in triangular facets. Either these facets represent the dip slope of very steeply inclined cuestas rising from the floor of the Limon Valley toward the Limon fault or else they are the result of a second parallel fault a short distance east of the major fault-plane.

Farther to the south, in the vicinity of Rincon and Tatarenda, I had opportunity to penetrate the Sierra de Limon by ascending one of the valleys which notch its eastern front. In that locality the range is margined by steeply inclined cuestas, the dip slopes of which rise from the Limon Valley floor toward the west at high angles. These slopes do not ordinarily continue to the highest summit of the range, but terminate against the fault-scarp, which is here well within the mountains, and beyond which rugged ridges and peaks rise several hundred feet higher to form the crest of the sierra. In places small remnants of what appear to have once been more extensive dip slopes, inclined downward toward the west on the west side of the fault-plane, may be observed high among the summit ridges.

Sierra de Charagua.—The Sierra de Charagua is a long, narrow, sharp-crested mountain ridge extending in a broadly crescentic curve from a point approximately in latitude $19^{\circ} 5'$ south, longitude $63^{\circ} 22'$ west to a point in latitude $21^{\circ} 18'$ south, longitude $63^{\circ} 9'$ west. Throughout the entire distance of 85 miles along the axis of the mountain ridge its width is approximately 4 miles. It is the most easterly of the Front Ranges of the Andes. Both to the north and to the south the other front ranges are distributed *en echelon*, with each successive range a few miles farther to the west than its predecessor in line. Its eastern slope rises abruptly from the margin of the lowlands of eastern Bolivia; its western



FIGURE 4.—*Sierra de Charagua, looking northward*

This view is taken from a col half a mile south of Rio Charagua, on the west side of the range. The steeply inclined hogbacks are composed of Tacuru sandstone.

side overlooks in a similar way the intermontane depression which separates this range from the next to the west.

Throughout nearly its entire length the accordance in elevation of higher ridges and peaks of the Sierra de Charagua is such that from a distance the sky-line formed by this range is very even. Its summit has an estimated altitude of 4,500 to 5,000 feet above the sea; the surface of the lowland along its eastern foot is close to 2,700 feet in elevation, while the intermontane depression on the west is generally between 3,200 and 3,600 feet. For long distances along both sides of this sierra there are numerous dip slopes formed by resistant strata pitching away from the axis of the mountains at high angles. These make rank after rank of hogbacks, which in most localities decline in elevation regularly from the innermost to the outermost (see figures 3 and 4). The steep hillsides are carved by youthful drainage systems and trenched by narrow ravines with unusually high gradients. The alternation of shale and sandstone affords abundant opportunity for the development of landslides, and these in most places are responsible for many details of the topography.

The summit elevations of the Sierra de Charagua are rounded rather than serrate. In places the mountain crest is a horizontal line formed by the truncation of the resistant inclined beds, but more commonly it is a succession of rounded knobs with an occasional sharp peak. There are no dip slopes on the very summits of the range, but rather the mountain crests are the result of the erosion of the inclined beds and the truncation of the wrinkled strata. There are occasionally gently sloping upland surfaces, but these bevel the upturned sediments and are ordinarily surrounded by slightly higher rounded knobs.

The range is traversed by the gorges of four master streams with courses approximately at right angles to the major axis of the range. Named in order from north to south, these are: Tacuru Creek, Saipuru Creek, Rio Charagua, and Rio Parapiti. In crossing the sierra, each flows through a remarkable canyon, with narrow floor, rarely wider than the stream bed and with steep rugged walls towering to elevations of 1,500 feet or so above the valley bottom (see figure 5). Tacuru Creek rises among the hogbacks along the west margin of the sierra and flows thence, in a slightly meandering course, through the central portion of the range and past the hogbacks of the eastern side until it reaches the wooded lowlands east of the mountains. Here its channel is choked by gravels and boulders which cause it to spread out in numerous distributaries over a broad floodplain. The other three streams all have their sources in or west of the intermontane depression which separates the Sierra de Charagua from the next ranges to the west. Traversing this



FIGURE 5.—*Gorge of Rio Saipuru*

This is one of the four streams which flow eastward through the Sierra de Charagua.

depression, their valleys are broadly open, with gentle slopes and extensive floors—typical late mature or early old age topography. Downstream each plunges through a narrow portal in the outer line of hogbacks along the west flank of the sierra and enters a narrow gorge, somewhat more sinuous than that of the Tacuru, but similarly directed, in general at right angles to the trend of the range. All these streams leave the mountains through portals which break the eastern line of hogbacks, and then flow with diminishing velocity across the plain beyond. Of the three, the Parapiti is the largest, and to it the waters of the other two are confluent during the wet season.

Sierra de Mandiyuti.—The Sierra de Mandiyuti extends in a broad curve, convex toward the west, from latitude $20^{\circ} 15'$ to latitude $20^{\circ} 40'$. It is flanked on the west by the Sierra de Chireti, the east margin of which rises abruptly just beyond the western slopes of the Mandiyuti range. To the east, there is a broad intermontane lowland, 5 to 15 miles in width, which intervenes between this range and the neighboring sierras which parallel it. Above this lowland belt the eastern slopes of the Sierra de Mandiyuti rise abruptly to a height of 2,000 feet, forming a magnificent fault-scarp. To the north this escarpment becomes irregularly lower until it almost disappears, and for a space of about 3 miles is represented merely by a line of low hills. Still farther northward the escarpment again becomes prominent, and there it forms the east margin of the Cuestas de Pipi. West of Cuebo the Mandiyuti range is extremely rugged, with numerous steep-sided, narrow canyons and ravines and occasional serrate peaks, which in general display a rough accordance in summit elevation. Two miles west of the Mandiyuti escarpment this irregular topography gives place to a series of comparatively regular hogbacks and cuestas whose gentler western slopes conform to the dip of the resistant sandstones of which they are composed. Two miles farther to the west there is another abrupt escarpment, in this instance about 1,200 feet high, trending north and south and rising to the summit of the rugged Sierra de Chireti.

The Mandiyuti range is traversed from west to east by Rio Cuebo and its largest tributary, Mandiyuti Creek. The headwaters of these streams rise among the gently inclined hogbacks near the western margin of the range. Toward the east they flow directly across the strike of the beds, cutting through successive hogbacks in comparatively narrow portals. In the irregular, rugged hills near the eastern front of the range, Mandiyuti Creek and Rio Cuebo flow through deep, steep-walled gorges. At one point the first mentioned stream plunges over a picturesque waterfall more than 200 feet in height. Here the walls are so steep that the trail

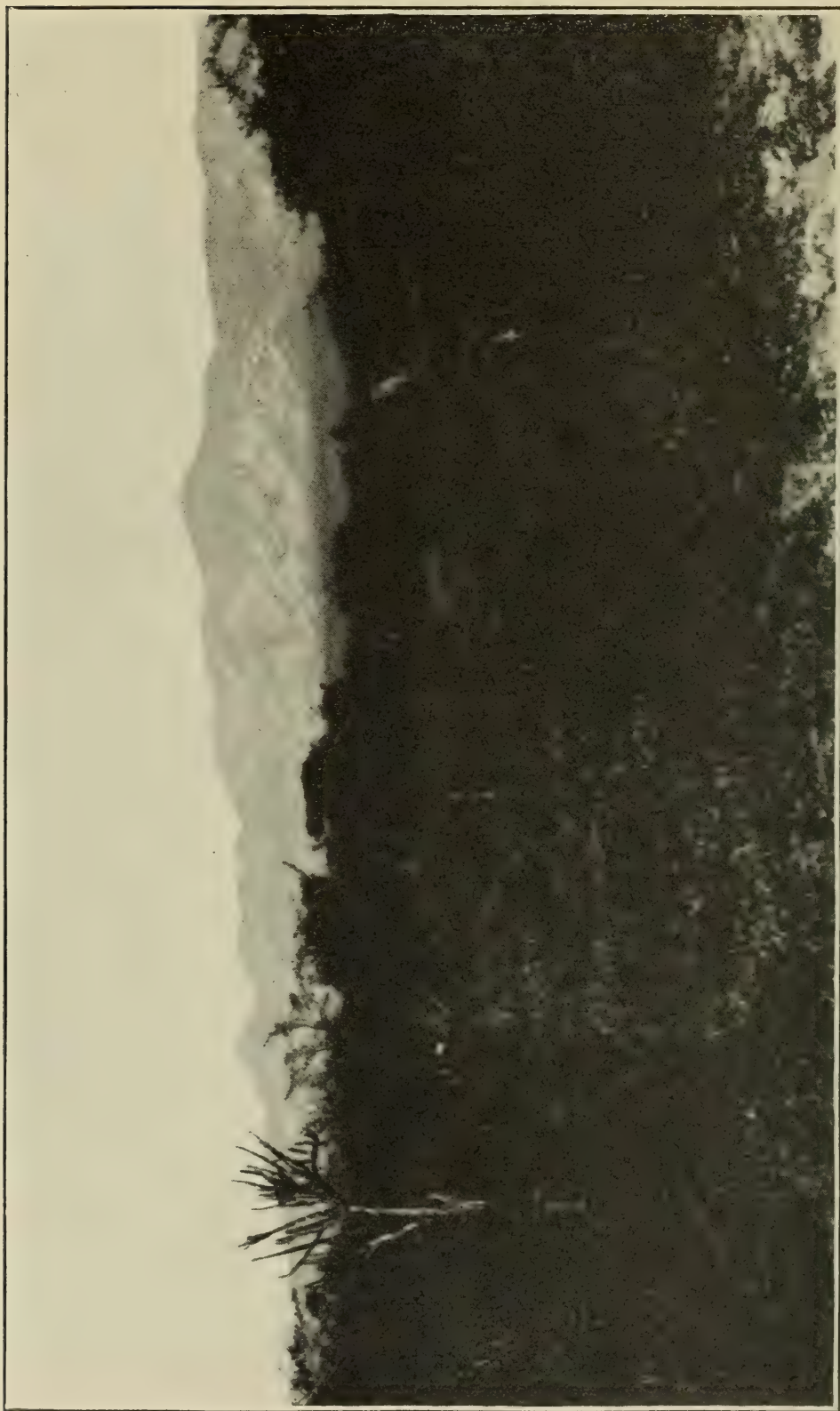


FIGURE 6.—*North End of the Sierra de Aguaraque*

View from the west, near Ibo.

climbs a thousand feet out of the canyon and across a high ridge a half mile north of the stream bed.

Sierra de Guarui.—About 20 miles west of the southern portion, of the Sierra de Charagua there is a parallel, but much shorter, range, known as the Sierra de Guarui. Among its unnamed peaks is the highest summit along the eastern front of the Andes, with serrate crest at an altitude of slightly over 6,000 feet. The whole sierra is exceedingly rugged in its youthful topography; its eastern margin is a bold fault-scarp which rises almost sheer for ten or twelve hundred feet above the floor of the broad lowland belt occupied by the Rio Guarui, which borders the range on the east and intervenes between it and the western back-slope of the Cuestas de Pipi. Ten to 15 miles south of Rio Parapiti there are numerous irregular hills of almost mountainous dimensions which clog this intermontane depression and connect the Sierra de Guarui with the northwest part of the Sierra de Mandiyuti.

Sierra de Aguarague.—The Sierra de Aguarague extends from a point in latitude $20^{\circ} 25'$ south to latitude $22^{\circ} 45'$, a distance of nearly 170 miles. It is the front range of the Andes throughout its entire length and overlooks the plain stretching eastward to the Paraguay River. The mountain summits rise abruptly above this plain to altitudes of about 4,500 feet. In certain places the mountain front is a sheer cliff, unbroken by erosion, rising almost vertically toward the higher summits. Elsewhere the eastern front of the mountains is formed by steeply inclined hogbacks, the dip slopes of which are conspicuous features of the topography. There is a rather striking accordance in summit elevation of the higher ridges and peaks throughout the entire extent of the sierra. At the north its heights decline gradually and blend into the plain near Boyuibi, about 10 miles southwest of the southern end of the Sierra de Charagua. At the south there is a similar descent to the plain which extends southward past Embarcacion.

Southwest of the Sierra de Aguarague is a narrow intermontane lowland, at an elevation of about 3,000 feet above sealevel, which separates it from the Sierra de Vitiacua. Its topography of undulating hills is similar to that of the plain east of the mountains. The northern part of this lowland in the vicinity of Ibo is shown in figure 6. In this same view the western slopes of the range, with their steeply inclined hogbacks dipping toward the west, may be observed in the distance. I have not observed the western slopes of this sierra south of Rio Vitiacua, but it is my understanding from the local inhabitants that the intermontane lowland continues southward and everywhere separates the Sierra de Aguarague from the more westerly ranges of the Andes.

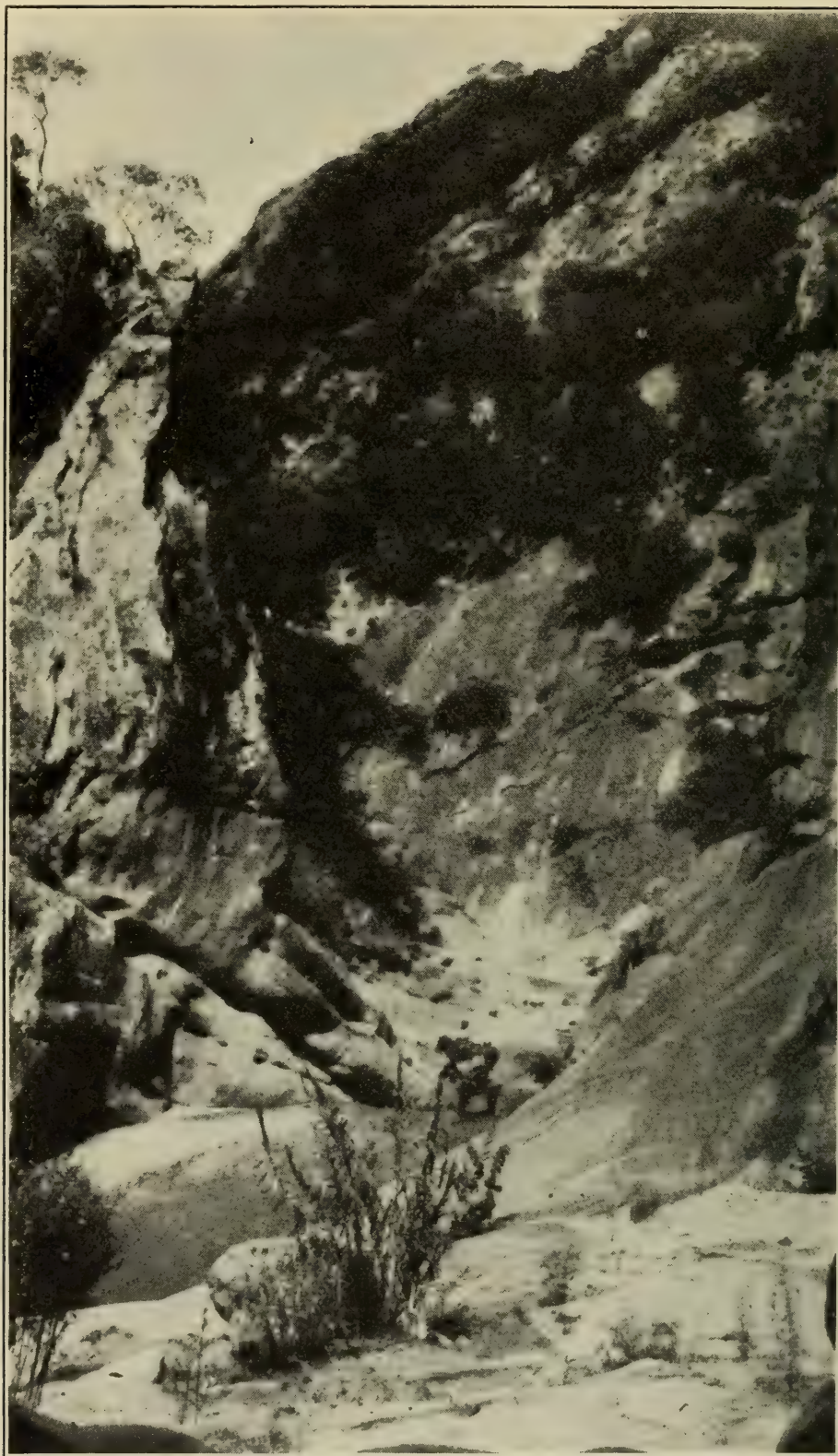


FIGURE 7.—*Canyon of Rio Vitiacua, in the Sierra de Aguarague*
The cross-bedded sandstones are a part of the Bermejo series.

The Sierra de Aguarague is traversed by the canyons of two rather large streams: Rio Vitiacua in latitude $20^{\circ} 50'$ and Rio Pilcomaya, near Villamontes, in latitude $21^{\circ} 15'$. It is also dissected by the ravines and gorges of many smaller streams which head within the narrow mountain range. The canyons of all these streams are very narrow and steep-walled; that of Rio Vitiacua is shown in figure 7. At one point in this canyon the walls close in so narrowly that there is not room for a trail during the rainy season and progress within the canyon is barred. This point is known locally as El Chorro and is shown in the photograph which forms figure 8. Here the trail leaves the stream bed and climbs up a steep tributary valley to La Loma, a saddle in the mountain ridge 600 feet above the canyon floor, beyond which the descent to the floor of the main canyon is equally as abrupt as was the ascent. Most of the larger streams in the Sierra de Aguarague, like those in the other ranges of the region under discussion, flow transversely to the longer axis of the range. Some, like the Rio Vitiacua, show a rather unusual adjustment to the structure, so that they flow for distances of a quarter mile or so along the strike of the beds, then turn abruptly and continue at right angles to the strike for a short distance, only to turn once more at right angles to flow along the strike in the opposite direction to that previously followed. Thus what presumably were once graceful meander curves are now a series of angular patterns along which the stream zigzags across the range.

The Quebrada de Los Monos, just south of Rio Pilcomayo, is unique among all the stream valleys which we observed, although there are probably three or four other similar valleys in the Sierra de Aguarague. This quebrada runs along the strike of the beds for many miles, instead of cutting across them from west to east. It is a quarter to a half mile in width and is carved in comparatively soft shales exposed along the axis of the Aguarague anticline. After flowing northward for 5 or 6 miles in this broad valley, the stream turns abruptly toward the east and plunges into a steep-walled gorge, through which it traverses the eastern half of the range. Beyond the portals of this gorge (see figure 9) the brook meanders across the plain at the foot of the sierra and eventually is tributary to Rio Pilcomayo.

Sierra de Vitiacua.—Between the north end of the Sierra de Aguarague and the south half of the Sierra de Mandiyuti there is a third range, the Sierra de Vitiacua, which parallels the Aguarague range and is separated from it by a lowland 4 or 5 miles in width. This range rises near Ibo as a line of low hills, true *cuestas* formed by the resistant sandstones of a tilted fault block, with a northward trending escarpment on the east. Toward the south these hills increase in height to form the mountain

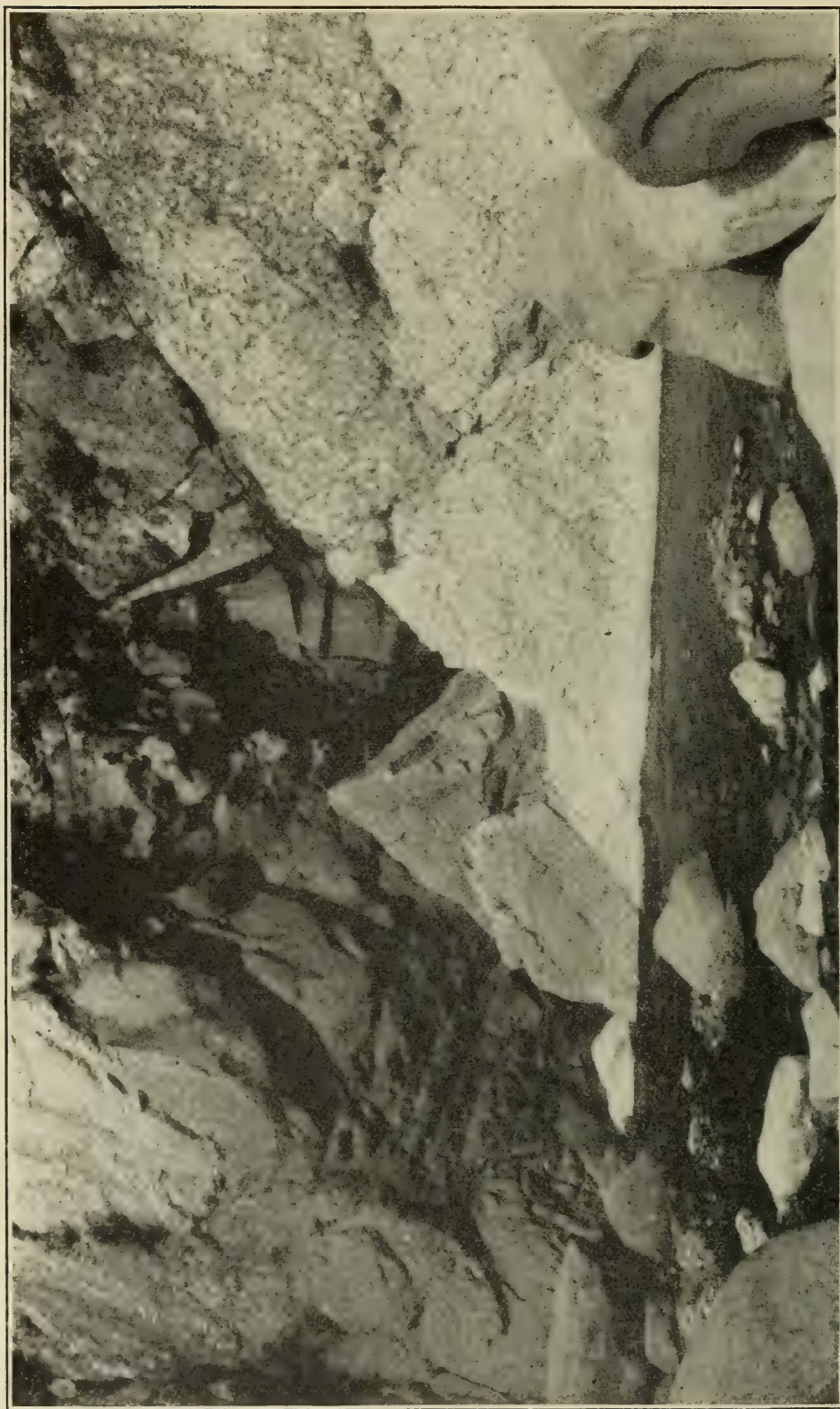


FIGURE 8.—*El Chorro, in the Canyon through which Río Vitiacua traverses the Sierra de Aguaraque near Machareti*
The nearly vertical barrier through which the stream has broken the narrow passage at the left of the center is a quartzitic bed in the Oquita formation.

range with summits 2,000 feet above the adjacent lowlands and with a magnificent cliff rising sheer along the eastern margin. South of Cangapi this fault front is partially concealed by a series of eastward-dipping *cuestas* which near Vitiacua rise well toward the crest of the *sierra*.

THE CHACO

The Bolivian Chaco stretches eastward from the front of the Andes to the Paraguay River. Although the region of the Chaco is ordinarily referred to as a lowland plain, its monotony is broken by several groups of hills and many isolated elevations. Most of the area is unexplored, but that portion adjacent to the main routes of travel eastward and southward from Santa Cruz is fairly well known.

Between Santa Cruz and the Rio Grande there is a flat plain averaging 1,400 feet in elevation, marked by low hillocks 20 to 100 feet in height, which once were sand-dunes, the migration of which has been stopped by the growth of vegetation or by changing climatic conditions. The trees are largely confined to these low mounds, and, as there is little surface drainage, the intervening swales are generally converted in rainy weather into shallow ponds and marshes. There is nothing, either in topography or drainage, to indicate the character of the underlying rocks. A few miles east of the trail leading southward in front of the Cordillera there are occasional live dunes, still restless beneath the shifting breezes of the plain.

The margin of the Chaco, within 3 miles of the mountain front, is much more broken and irregular in its topography. Hills 400 feet in height are separated by steep-sided canyons, and nearly everywhere there is a dense growth of trees, underbrush, and vines. The interstream areas are broad and not greatly dissected by gullies. In many localities they display the undulating topography of ancient dune country. Elsewhere they seem to be the dissected remnants of a piedmont alluvial plain. The stream-cuts are all developed in comparatively recent materials, wind-blown sand or stream alluvium, and in no place do they reveal the older underlying beds.

South of the Rio Grande the east front of the Sierra de Charagua overlooks the western margin of the Chaco, which is there generally covered with a rather scanty forest. Close to the Cordillera the interstream areas are generally dotted with low hills, which have a definite linear trend parallel to that of the *sierra*. These are for the most part miniature hogbacks formed of strata a little more resistant than the others and inclined gently toward the east, away from the mountains. Similar conditions maintain along the front of the Sierra de Aguarague. The low undulat-



FIGURE 9.—*Gorge in the eastern half of the Sierra de Aguarague*

The stream which drains the Quebrada de Los Monos through this gorge breaks across the Bermejo and Tacuru sandstones on the east flank of the Aguarague anticline.

ing hills which at many places parallel this range are of considerable prominence in the vicinity of Tareiri, where they coalesce into a ridge 200 feet in height, paralleling the sierra for many miles and passing just east of the village.

Farther south, near Yacuiva, there is a group of rather prominent hills, known as the Cuestas de Ipahuazo, situated 8 to 12 miles east of the Sierra de Aguarague. These hills are heavily wooded and among them there are few exposures of underlying rocks. The generally softened, rolling topography offers many suggestions of alignment parallel to the trend (north 20 degrees east) of the neighboring sierra. The western margin of these hills is sharply defined by dip slopes, 150 to 300 feet high, which rise from the broad shallow valley traversed by the trail from Palmar, past Yacuiva, to Aguaray. The hills are doubtless a response to the deformation of the resistant sandstones and may be structurally the continuation of the Sierra de Charagua, although topographically they are far removed from that mountain range.

INTERMONTANE LOWLANDS

Between the northward-trending mountain ranges above described, there are intermontane depressions, 3 to 15 miles in width, which stretch for long distances north and south. These lowlands display in general an undulating topography with moderate relief. With the exception of the prominent cuestas which occupy certain of these depressions, the elevations on them are quite irregular in distribution and have soft, rounded outlines, in striking contrast to the sharp profiles of the adjacent sierras. South of Cangapi, where the streamlets which drain these intermontane depressions are tributary to Rio Vitiacua, the topography is much more broken than in the north part of the area under discussion. Because of the lower baselevel of Rio Vitiacua and the other tributaries to the Pilcomayo, the interstream areas there are carved into fairly sharp ridges separated by youthful ravines, suggesting greater erosional efficiency on the part of the Pilcomayo and its tributaries than that displayed by the affluents of Rio Grande.

The intermontane depression west of the Sierra de Charagua is modified by two lines of prominent hills. The eastern group forms the Cuestas de Oquita, the northern extension of which is locally referred to as the Cuestas de Taimbermi. These hills are separated from the Sierra de Charagua on the east by a long, narrow lowland about 3 miles in width, drained by various tributaries to Rios Saipuru, Charagua, and Parapiti. Their east margin is a bold, rugged cliff which extends for at least 40 miles from a point far to the north of Taimbermi southward beyond Rio

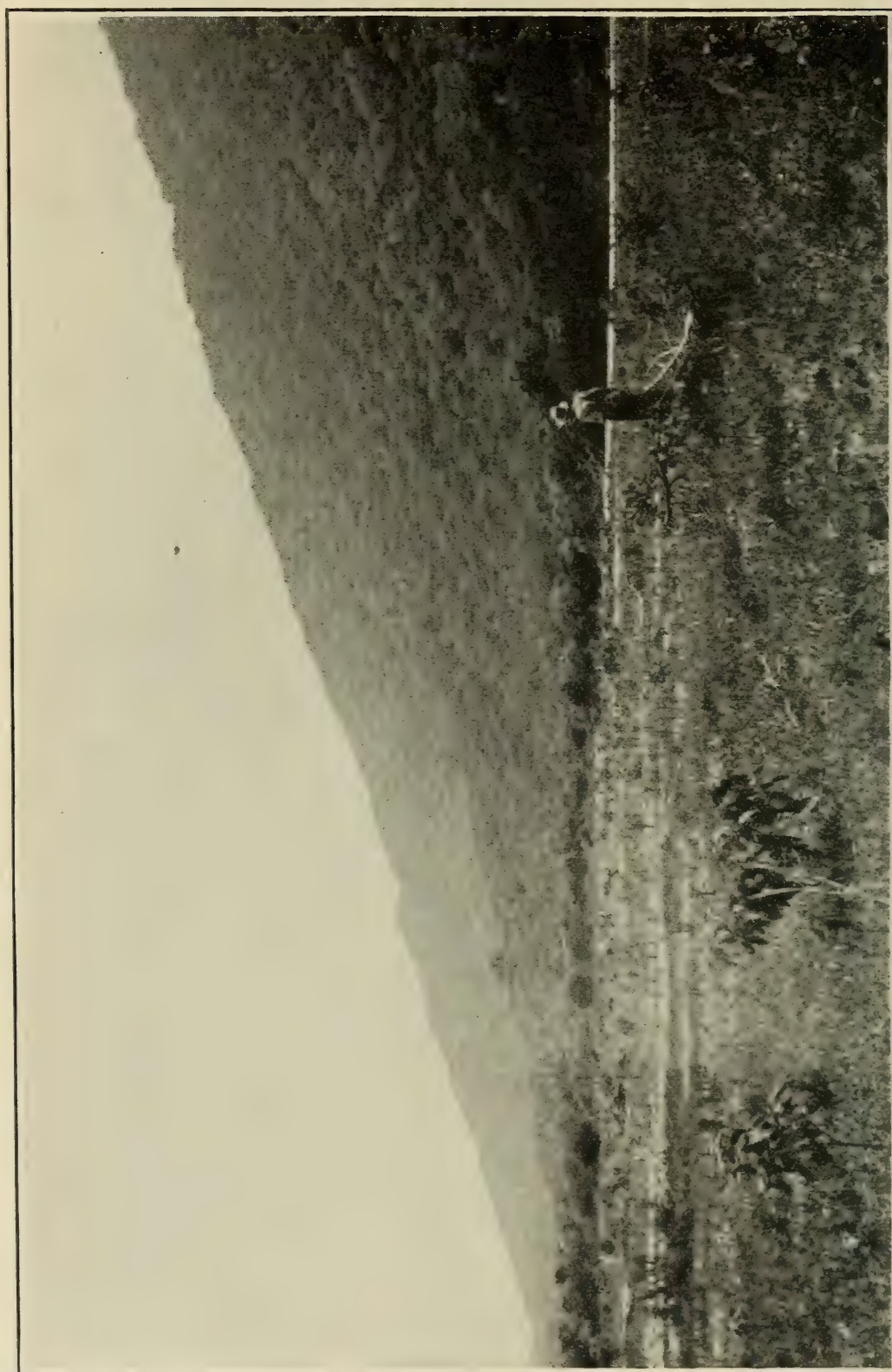


FIGURE 10.—*Dip Slope of the westernmost Hogback of the Cuestas de Pipi*

This dip slope is on the east side of the Guarui Valley.

Parapiti. This escarpment rises abruptly to an elevation of about a thousand feet above the lowland and is broken at long intervals by such picturesque gorges as that traversed by Rio Parapiti, approximately at right angles to the trend of the hills. The crest of the hills above this cliff is somewhat uneven and broken, but throughout nearly their entire length the summit elevations are closely similar. To the west of this easternmost ridge there are typical hogbacks with steeply inclined dip slopes on the west and rugged eroded cliffs on the east. Successive ridges toward the west are lower in altitude and display more gentle dip slopes, until finally the westernmost *cuesta* blends almost imperceptibly into the undulations of the plain which separate this group of hills from the next ridges on the west.

In the vicinity of Rio Parapiti this lowland is about 10 miles in width and extends to the east front of the *Cuestas de Pipi*, a group of hills situated a few miles west of Pipi on the Rio Parapiti. Their eastern margin is a steep escarpment flung in a broad, sweeping curve from north to south. It rises abruptly to elevations of about 1,500 feet above the intermontane lowland and is broken at only one point, where Rio Parapiti has carved a steep-walled canyon which cuts across the line of hills from west to east. The eastern rampart of these *cuestas* displays a close accordance in summit elevation throughout the greater part of its length. This eastern ridge, with its steep east front, is paralleled on the west by a succession of four or five other ridges, separated from it and from each other by youthful valleys. These are in reality hogbacks, for the western slope of each conforms closely to the dip of the resistant sandstone strata of which each is formed. The eastern faces are generally much steeper, and thus the valleys between successive ridges are asymmetrical. The westernmost hogback forms the eastern slope of the Guarui Valley and is shown in figure 10. Rio Parapiti cuts through the successive ridges in a steep-walled gorge, which is from 100 to 300 yards in width in the narrows formed by each successive hogback, but broadens to a width of half a mile or so in the inter-hogback areas. Tributary streams, such as Wirendi and Guarui creeks, flow roughly parallel to the trend of the hogbacks and occupy valleys cut along the strike of the weaker strata.

DRAINAGE SYSTEM

The larger streams of this area all flow eastward with little apparent regard for existing topographic features. The two largest, Rio Grande and Rio Pilcomayo, have their sources far to the west, in the heart of the Cordillera Oriental. Flowing east, they cut through the successive sierras and *cuestas* in exceedingly rugged canyons and narrow gorges,

which are a complete contrast to the broad late-mature valleys occupied in the intermontane lowlands. The more northerly of the two, the Rio Grande, is eventually tributary to the Amazon, while the Rio Pilcomayo contributes its waters to the Paraguay and River Platte. Other rivers, such as the Saipuru, Charagua, Cuevo, and Vitiacua, rise within one of the inner sierras and flow thence across the lowlands through broad, open valleys until they reach the western side of the next ridge to the east. Through it they invariably make their way in extremely youthful canyons. Beyond the mountain front the majority of the smaller streams lose themselves among the sand hills of the Chaco.

Except in time of unusually low water, Rio Grande and the Pilcomayo can not be forded, but may be passed in the ferries situated at the crossings of the main trail between Santa Cruz and Yacuiva. The other rivers may be forded almost anywhere along their courses, although certain of the fords are dangerous or even impassable at times of high water, during the rainy seasons.⁵

PHYSIOGRAPHIC HISTORY

It is obvious from the foregoing description of the physiography and drainage system of this region that its stream pattern was inherited from a previous erosion cycle. The modern streams are neither consequent on, nor adjusted to, the existing land surface and geologic structure. Two alternative theories should be considered: The master streams may be antecedent; they may be following courses determined before the episode of crustal deformation responsible for the folds and faults of the sierras and cuestras, courses which they maintained regardless of the crumpling of the mountain ranges directly athwart their paths. Or the rivers may be superimposed. Subsequent to the crumpling of the strata into approximately their present attitude, the entire region was reduced to base level and the easterly courses of the master streams were developed without regard to the structures beneath the peneplain, structures which were etched in bold relief subsequent to the rejuvenation of the streams coincident with the regional uplift which inaugurated the existing cycle of erosion.

In the preceding descriptions of the sierras and cuestras in this region, emphasis has been frequently placed upon the close accordance in summit level within each mountain group. The comparatively plain surface projected through these summits rises gently toward the west, as each successive range of the Andes system is a few hundred feet higher than

⁵ K. F. Mather, 1922 b.

its eastern neighbor. This regular increase in summit altitude from range to range adds much strength to the hypothesis that summit elevations within each sierra are remnants of a former lowland plain. At a very few localities there are upland surfaces of the plateau or mesa type which may be considered as larger remnants of that same quondam lowland. One of these is especially worthy of mention. It is situated about half way between the canyons of Rio Saipuru and Rio Charagua, high on the eastern slope of the Sierra de Charagua. Its surface has an area of about a square mile and bevels the upturned sandstone strata. It is evidently an erosion feature. The highest summits of the range rise as jagged peaks 300 or 400 feet above it. Elsewhere in the same mountain group there are occasional upland surfaces with gentle slopes which bevel the upturned sediments and are ordinarily surmounted by slightly higher rounded knobs. These upland flats are evidently erosion forms developed by streams with low gradient traversing an old-age topography.

Again, in the Sierra de Aguarague there are certain topographical features suggesting former peneplanation. Between Camatindi and Tarairi the summit of this range for a dozen miles is an eastward-dipping hogback. The remarkably smooth dip slope of this hogback rises to a crest which for long distances is as regular as a roofline. Above this rooflike ridge there are somewhat higher peaks at either end, such as that shown in figure 11; these were doubtless monadnocks rising above the peneplain which beveled the inclined strata.

Although the data are not as complete as might well be desired, what few facts are known all seem to point toward a two-cycle origin of the present topographic features. At a comparatively recent date in geologic history, subsequent to the crumpling and faulting of this region, an old-age topography seems to have been developed quite generally throughout the territory now occupied by the mountain ranges. Rivers meandered across the lowlands toward the east in much the same courses as those now followed by the master streams. That cycle of erosion was closed by regional uplift, which warped the surface slightly and elevated its western margin somewhat higher than its eastern. The rejuvenated streams quickly incised their valleys and reduced their channels to the new baselevel. In the areas of weaker rocks, wide valleys were quickly carved and with the aid of the tributary streams the modern intermontane lowlands were developed. Wherever more resistant strata had been brought above drainage by folds and faults, the larger streams have thus far been confined in the most youthful of canyons, and the hogback hills and serrate ranges have towered above their surroundings

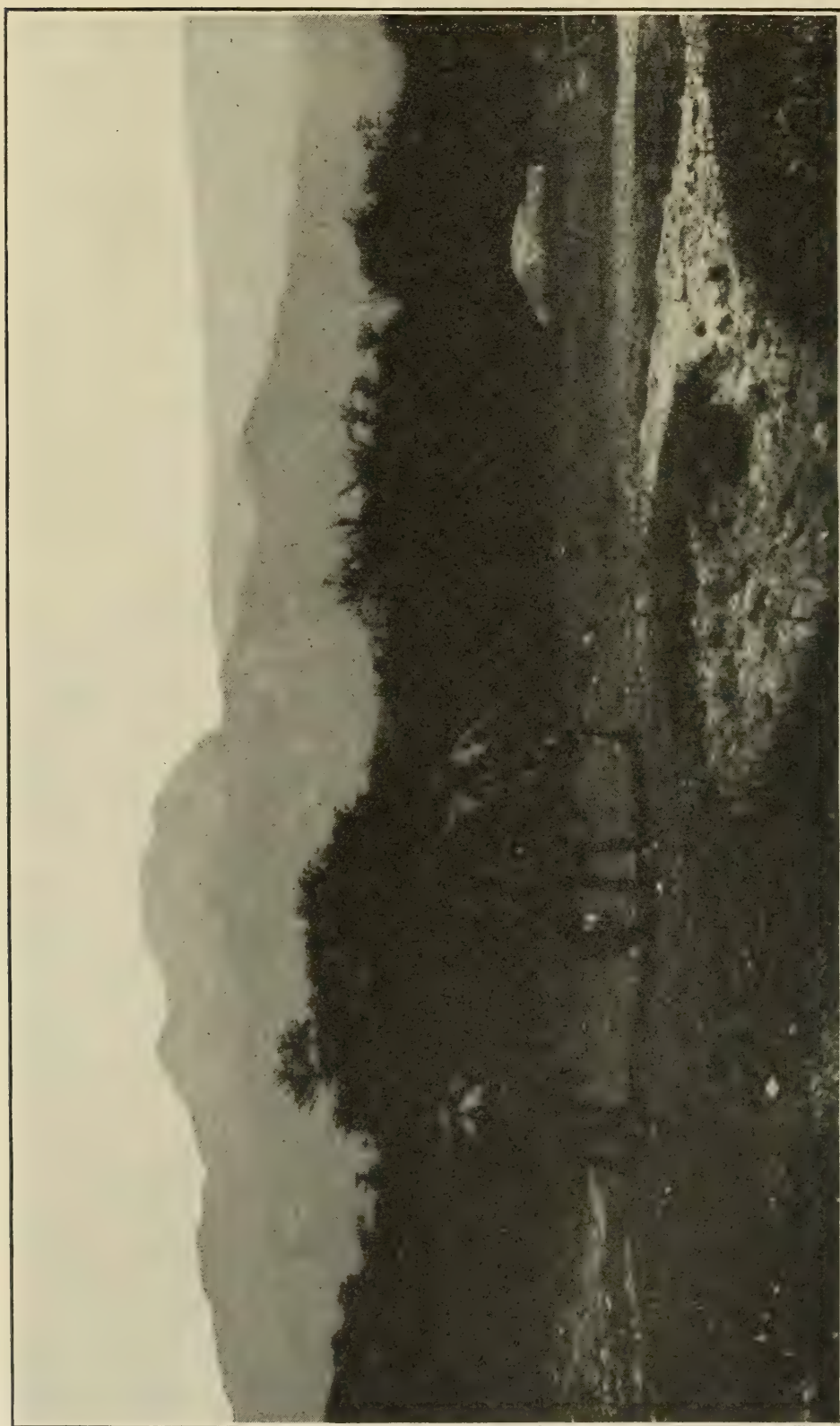


FIGURE 11.—*Sierra de Aguaraque*

As seen from the plain near Tarairi. At the left of the center is Mount Tarairi, and at the right is a portion of the "roof-tree" which forms the summit of the range for a dozen miles, between Camatindi and Tarairi.

because of the great differences in resistance offered by the weaker and stronger formations. At some localities within the various mountain groups the former graceful, meander curves have been changed into sharply angular chevrons, so that canyons like the Vitiacua Gorge zigzag here along the strike and there at right angles to it in response to the attempt made by the rivers to traverse the mountains along the easiest channels.

STRATIGRAPHY

GENERAL STATEMENT

The entire area of the Front Ranges of the Andes is underlain by sedimentary rocks of late Paleozoic, Mesozoic, and Cenozoic age. There are no igneous nor metamorphic rocks exposed within these mountains. Beneath the lowlands, both within the Cordillera and on the plains to the east, the solid rocks are nearly everywhere concealed beneath a veneer of stream gravel, wind-blown sand, and soil, but exposures along the mountain slopes and cuesta fronts are excellent, so that an accurate idea of the succession of strata beneath the entire area may be obtained with comparative ease. To facilitate the study and description of the geology of this region, concerning which very little reliable information has been published, the sedimentary strata have been divided into the following formations and series, to which local geographic names have been applied. The formations are named in ascending order, the oldest at the bottom.

Quaternary gravels, sands, clays, and silts.

Unconformity.

Tatarenda formation; soft sandstones, shales, unconsolidated sands and clays, occupying in general the lowland areas; probably Tertiary; 3,000 to 4,000 feet thick.

Unconformity.

Tacuru formation; resistant sandstones and interbedded shales, the "hogback makers" along the margins of the sierras; late Mesozoic or possibly in part early Tertiary; 2,000 to 4,000 feet thick.

Unconformity.

Vitiacua limestone and chert; Upper Trias or Lias; 10 to 100 feet thick.

Bermejo series; Permo-Triassic; comprising the following formations:

Machareti formation; massive, cross-bedded sandstones and interbedded non-fissile shales and clays; 800 to 1,600 feet thick.

Mandiyuti conglomerate; massive conglomerates, grits and sandstones, with interbedded sandy shales; predominantly red; in large part fluvio-glacial; 1,500 to 3,200 feet thick.

Oquita formation; extremely variable sandstones and shales, some of which are probably glacio-lacustrine; at many localities, including lavender or maroon sandy shales; 1,000 to 2,000 feet thick.

Unconformity.

Totora series; Devonian; including in the northern part of the area the Espejos formation and in the southern part the Los Monos shale.

Los Monos shale; blue gray to black, fissile shale with interbedded micaceous sandstones; base not exposed; more than 1,000 feet thick.

Espejos formation; dark bluish or greenish black carbonaceous fissile shale with intercalations of dark, fine-grained, brittle limestone in beds two or three inches thick; total thickness unknown.

ESPEJOS FORMATION

The Espejos formation was first described by Heald and Mather in a report upon the geology of the eastern Andes a short distance north of the area now under consideration.⁶ The type locality is in the Espejos quebrada, in the Sierra de Santa Cruz where the dark carbonaceous shales and thin limestone strata carry trilobites and brachiopods of Devonian age.

In the Front Ranges of the Andes south of the Sierra de Santa Cruz, only one small outcrop of this formation was observed. That outcrop is in the quebrada of Rio Tacuru, in the northern part of the Sierra de Charagua. It is probable that other exposures of the Espejos beds occur just beyond the western margin of the area traversed during the reconnaissance studies on which this report is based. It is also possible that the Espejos formation is at the surface within the gorge through which Rio Parapiti traverses the Sierra de Charagua, for it is likely that much lower beds are exposed within that gorge than along the floor of the parallel canyon of Rio Charagua. It is doubtful, however, whether there are other exposures than these anywhere else within the region under discussion.

The beds exposed in the Tacuru quebrada are dark bluish or greenish black, richly carbonaceous, fissile shale with intercalations of dark, fine-grained, brittle limestone in beds 2 or 3 inches thick. In all respects they are identical with the Espejos formation at the type locality in the Espejos quebrada and elsewhere in the Sierra de Santa Cruz, north of the eighteenth parallel; the lithology is so distinct that there can be no question of the correctness of the correlation, although no fossils were found in the Tacuru exposure.

In the Tacuru quebrada the Espejos beds are faulted against much younger strata, and the nature of the normal contact between them and the next younger formation has not been ascertained. In the Sierra de Santa Cruz, however, this contact is displayed as a great unconformity. In the region traversed by the trail from Cochabamba to Santa Cruz

⁶ K. C. Heald and K. F. Mather, 1922.

there is likewise a marked unconformity between the Totorá series, of which the Espejos formation is a part, and the overlying Bermejo series.

LOS MONOS SHALE

The oldest formation exposed within the Front Ranges south of the twentieth parallel is a succession of shales and intercalated sandstones, to which the name Los Monos shale is applied because of the excellent exposures in the Quebrada de Los Monos in the Sierra de Aguarague 5 miles southwest of Villamontes. Other outcrops of this formation have been observed in the gorge through which Río Vitiacua traverses the northern part of the Sierra de Aguarague near Machareti, and at the point where Río Parapiti emerges from its canyon through the Cuestas de Pipi, a few miles west of the town of Pipi. It is also probable that the lowest beds in the Sierra de Mandiyuti, at the locality shown in figure 12, where Río Cuevo crosses the Mandiyuti fault, and the lower strata exposed in the escarpment at the east side of the Cuestas de Oquita near Río Parapiti should be referred to this formation, although these beds are much more sandy than the strata at the type locality.

The Los Monos shale is blue gray to black, thin-bedded and fissile, containing an abundance of tiny flakes of muscovite mica and apparently rather rich in carbonaceous matter. Interbedded with the shale there are occasional layers of micaceous and argillaceous sandstone; toward the top of the formation these intercalations become more frequent and thicker; the shales also are more sandy and exhibit a dark brown color, while the interbedded sandstones are much coarser and even conglomeratic.

The base of the Los Monos shale has nowhere been observed and its thickness can not be stated. At the type locality the exposed beds aggregate a thickness of 1,000 to 1,200 feet.

In the Vitiacua gorge near Machareti about 800 feet of the Los Monos shale are exposed in the canyon walls immediately downstream from El Chorro. At this point the Vitiacua-Machareti trail regains the canyon floor, following its detour past the narrows. Here the Los Monos shales are more arenaceous and are interbedded with thin sandstones, but the general dark color, carbonaceous content, and abundance of mica make quite sure the correlation with the formation at its type locality.

No fossils were found in the Los Monos shale during the progress of the reconnaissance studies on which this report is based. Dr. Bonarelli, however, describes⁷ a trilobite, *Dalmanites* (?) *pentlandi*, and a pele-

⁷ G. Bonarelli, 1921, p. 54.



FIGURE 12.—*Lowest Beds in the Sierra de Mandiyuti*

These beds are exposed on the north side of Rio Cuevo, close to the fault at the east margin of the range. The fault-plane crosses the river a few yards downstream, beyond the right margin of the photograph; the Devonian beds shown in the picture dip toward the west.

cypod, *Nuculites* sp., which were obtained from dark shales in the Quebrada de Los Monos. These fossils were beyond doubt from the strata here named the Los Monos shale. According to Bonarelli, they indicate the Devonian age of the inclosing beds, which he correlates with the Icla shales, a formation which outcrops over wide areas in the Bolivian and Argentine territory to the west and southwest of the Front Ranges.

Dr. Bonarelli also describes the following fossils from the lowermost beds in the Sierra de Mandiyuti: *Rensellaria falklandica*, *Leptocoelia flabellites*, *Orthis pectinata*, *Rhynchonella?* sp., *Schizobolus* sp. This also is a Devonian fauna and its description confirms the tentative conclusion that the lowest beds in the Sierra de Mandiyuti are of similar age to those in the Quebrada de Los Monos. The greater amount of sand at the Mandiyuti exposures would suggest the possibility of close correlation between the strata there and the Huamampampa sandstones which overlie the Icla shales in the western part of the Cordillera Oriental.

Although in some respects the Los Monos shales resemble the Espejos formation, and the fossils found in each indicate their correspondence in age, it is thought wise to retain separate names for the two. The beds at the north contain a considerable percentage of limestone, which is entirely lacking from the southern localities. Should the two be proven contemporaneous when more detailed studies are made, it would probably be best even then to indicate the lithologic differences by individual formation names.

BERMEJO SERIES

Origin of the name and limit of the series.—The name Bermejo series was first applied by Heald and Mather (1922) to the thick series of sandstones, shales, and conglomerates intervening between the Totorá series and the Cajones limestone in the Cordillera Oriental, north of the eighteenth parallel. From these more northerly localities the beds have been traced with practical continuity into the region now under discussion.

The upper limit of the Bermejo series in the Front Ranges, south of the eighteenth parallel, has been placed at the lower surface of a limestone, or limestone and chert, formation which is believed to be correctly correlated with the Cajones limestone of the Sierra de Santa Cruz. This overlying limestone chert horizon is the "Horizonte Calcereo-dolimitico" of Steinmann and Bonarelli. According to Steinmann, the fossils in that formation suggest its Cretaceous age, but the more representative collections described by Bonarelli in his recent contribution (1921) un-

mistakably demonstrate that these beds are late Triassic or early Jurassic.

The only fossils found by us within the Bermejo series were indeterminate fragments of lingulas from beds overlying the fluvio-glacial Mandiyuti conglomerates in the northern part of the Sierra de Santa Cruz. The presence of glacial and fluvio-glacial beds among the Bermejo strata is in perfect harmony with the conclusion reached by Bonarelli and based on its stratigraphic relation to the underlying Devonian and overlying Liassic beds, that this thick series of clastic sediments is of Permo-Triassic age.

As here defined, the Bermejo series is the equivalent of Bonarelli's "Areniscas Inferiores" and Steinmann's "Formacion Petrolifera," and may be correlated with the lower part of the "Sistema de Salta" as defined by Brackebusch. Because of rather uniform differences in the lithology of successive beds within this series wherever the greater part of it is exposed, it has been divided into three formations, as follows:

Oquita formation.—This formation is exposed in each of the sierras and cuestras where detailed examinations were made. It is named from the type locality, in the eastern part of the Cuestas de Oquita, along the walls of the Parapiti gorge. It includes the sandstone and shales between the Devonian strata and the Mandiyuti conglomerate. Its thickness varies from about 1,000 feet, as exposed in the Quebrada de Los Monos, to about 2,000 feet, as in the Cuestas de Oquita.

The Oquita formation is dominantly sandstone, but includes a considerable amount of shale. It is extremely variable in composition, both with regard to the succession of beds at any one locality and with reference to the nature of any single bed when traced from place to place. Where its base is exposed, the lower beds of this formation are gray sandstone one-half to 2 feet thick, which are generally irregularly laminated or cross-bedded. These sandstones may be stained various shades of maroon or vermilion on weathered surfaces.

Above these basal sandy beds there is ordinarily a thick series of shales. In the northern part of the Sierra de Aguarague these shales are dark and micaceous, fissile or nearly so, and contain lenses and concretions of sideritic or limonitic material. Along the eastern front of the Cuestas de Oquita, near Rio Parapiti, these same shales are quite sandy and in places might better be called thin-bedded argillaceous sandstones. They are interstratified with beds of gray, or greenish gray, grit and fine pebbly conglomerate. Here, also, they contain an abundance of mica, but the sand grains are not very well sorted according to size. Similarly, in the Sierra de Mandiyuti this portion of the Oquita formation is thin-bedded, sandy and micaceous. The lowermost strata exposed in this

sierra are found in the valley of Rio Cuevo at the point where it emerges from its mountain canyon, 3 miles west of Cuevo. The lowest beds on the upthrow side of the Mandiyuti fault at this point are Devonian sandstones and sandy shales, and the contact between them and the base of the Oquita formation was not definitely located. The lower third of the Oquita formation has not been observed in the Sierra de Charagua, although it may be exposed in the gorge of Rio Parapiti.

The middle third of the Oquita formation, at the type locality in the Cuestas de Oquita, is composed chiefly of cream and red sandstone, in somewhat thicker and more irregular beds than the gray strata which underlie them. There is less mica in this portion of the formation and the sand grains are much more evenly sized. In the Sierra de Aguarague, at this same stratigraphic horizon, there are massive white sandstones which in places have a resistance to erosion almost equivalent to that of quartzites. These beds form the narrows at El Chorro, in the Vitiacua canyon (see figure 8), and they likewise may be recognized in the Quebrada de Los Monos between 200 and 400 feet above the base of the formation. At that locality they are variegated and streaked with many shades of red on weathered surfaces.

The resistant sandstones midway in the sequence of beds referred to the Oquita formation are overlain in the northern part of the Sierra de Aguarague by a peculiar structureless clay which outcrops immediately upstream from El Chorro, in the Vitiacua gorge. This clay is dark gray, rather firmly indurated, and contains occasional tiny pebbles of quartz or igneous rock. In places it is finely laminated in a manner strongly suggesting the varve structure of glacial lake beds. The entire thickness of this member of the Oquita formation is about 300 feet. It was not observed at other localities than this.

The upper six or eight hundred feet of the Oquita formation at the type locality in the Cuestas de Oquita consist chiefly of thin beds of fine-grained sandstone and sandy shales which display a variety of tints of vermilion, maroon, and greenish gray. The sandstones contain much clay and are finely laminated as well as thinly bedded. The shales contain only a little less sand than the interbedded sandstones and are commonly in beds an eighth to a quarter of an inch in thickness. These strata are richly micaceous and in places contain carbonaceous material which is believed to represent finely comminuted vegetable matter. This member is the most persistent of those forming the Oquita formation and varies only slightly in thickness throughout the entire region from the Sierra de Charagua southward to the Rio Pilcomayo. In the gorge of Rio Charagua these strata are in somewhat thicker beds and are much

more prominently cross-bedded than at the type locality. The exposure in that gorge is at the point where the stream cuts across the crest of the Charagua anticline. South of the Pilcomayo in the Quebrada de Los Monos the upper 500 feet of the Oquita formation are much finer grained than the equivalent beds to the northward. Instead of sandstones, there are very thin-bedded and finely laminated, but not fissile, shales of a prevailing maroon or lavender shade. Near the upper limit of the formation, there is a dark blue to black member which contains occasional lenses of blue gray, non-crystalline limestone 2 or 3 inches thick.

The Oquita formation would, therefore, appear to be the result of sedimentation in a large basin to which streams were bringing material chiefly from the north or northeast. Conditions of accumulation within this basin must have been quite variable and may have run the entire gamut from fluvial to marine.

Mandiyuti conglomerate.—This is the most striking formation of the Bermejo series; it forms many of the rugged cliffs and much of the picturesque scenery in each of the sierras and cuevas which were surveyed. Its name is derived from the Sierra de Mandiyuti, in which range it is well developed and marvelously displayed. The lavish exposures in the canyon of Mandiyuti Creek below the falls form the type locality. At this place the Mandiyuti formation comprises a pebbly conglomerate member overlain by somewhat finer grained yellow sandstones, which are in turn overlain by an upper conglomerate member. Each member is approximately a thousand feet in thickness.

Elsewhere throughout the Front Ranges this formation is for the most part massively bedded conglomerate and grit, but it includes also a liberal percentage of sandstone and sandy shale. The majority of its beds display brilliant tints of various shades of red and purple; maroon, carmen, lavender, and vermilion are typical. Some of its strata, however, are green, gray, or white. The red tints are not alone due to weathering at the surface; rather, the formation is a series of true "Red Beds."

The conglomerates and grits contain a varied assortment of pebbles of all sizes and shapes. Quartzite, quartz, chert, and granitic igneous rocks are the most common kinds. Most of them are well rounded and polished by stream or current action, but in every locality there are many angular pebbles with faceted faces. Some of these are unquestionably shaped by glacial action. Most of the pebbles are small, but stones three or four inches in diameter are not rare, and in certain places boulders as great as 3 feet in length have been observed. The formation is evidently

a fluvio-glacial accumulation, composed of debris spread broadcast over a lowland area by streams issuing from melting ice. In part it may be lacustrine or even marine, but its materials have in the main been derived directly or indirectly from glaciers or ice-sheets. Doubtless it is genetically related to the tillite in the Bermejo beds, observed along the trail from Cochabamba to Santa Cruz,⁸ and to the glacial formations in the eastern Andes in northern Argentina, recently described by Keidel⁹ as being overlain by strata carrying the Gondwana flora.

The Mandiyuti conglomerate varies in thickness from about 1,500 feet in the north part of the Sierra de Aguarague to about 3,200 feet at the type locality in the Sierra de Mandiyuti. In most places it is between 2,000 and 3,000 feet thick. Individual beds as much as 250 feet in thickness occur in the midst of the formation at several localities. These display closely spaced, irregular laminations.

The Mandiyuti conglomerate is well exposed in the three canyons in the Sierra de Charagua, through which reconnaissance traverses were run, and evidently it forms the central massif of that mountain range throughout its entire length. No unusual features were noted in that sierra, although in general the formation is possibly somewhat more irregularly bedded there than elsewhere. The lower part of the Mandiyuti conglomerate is exposed in only one of the three gorges examined; in that one, the Charagua canyon, the formation is at least 2,000 feet thick. Approximately 1,500 feet of Mandiyuti beds are exposed in the gorge of Rio Saipuru, while Rio Tacuru has cut only 500 feet below the top of this formation.

Again, in the Sierra de Aguarague the Mandiyuti conglomerate forms the central portion of the range from end to end. Among the pebbles contained in the conglomerate members, cobblestones four or five inches in diameter, with undoubtedly glaciated surfaces, were noted at several places. In the Vitiacua gorge the Mandiyuti conglomerate is about 1,600 feet thick, while in the Quebrada de Los Monos its thickness was estimated at 2,500 feet. At the latter locality three distinct conglomerate horizons, separated by sandstone and shales, were noted.

In all probability, the Mandiyuti conglomerate is the source of the "few scattering fragments" of igneous rocks reported by Herold¹⁰ "to be found in the creek beds" and interpreted by him as having "been transported from the higher mountains of the Andes ranges . . . previous

⁸ Heald and Mather, 1922.

⁹ Juan Keidel: Observaciones Geologicas en la Precordillera de San Juan y Mendoza. Anales del Ministerio de Agricultura, Sec. Geol., etc., Tomo XV, no. 2. Buenos Aires, 1921, pp. 57-63.

¹⁰ S. C. Herold, 1920, p. 556.

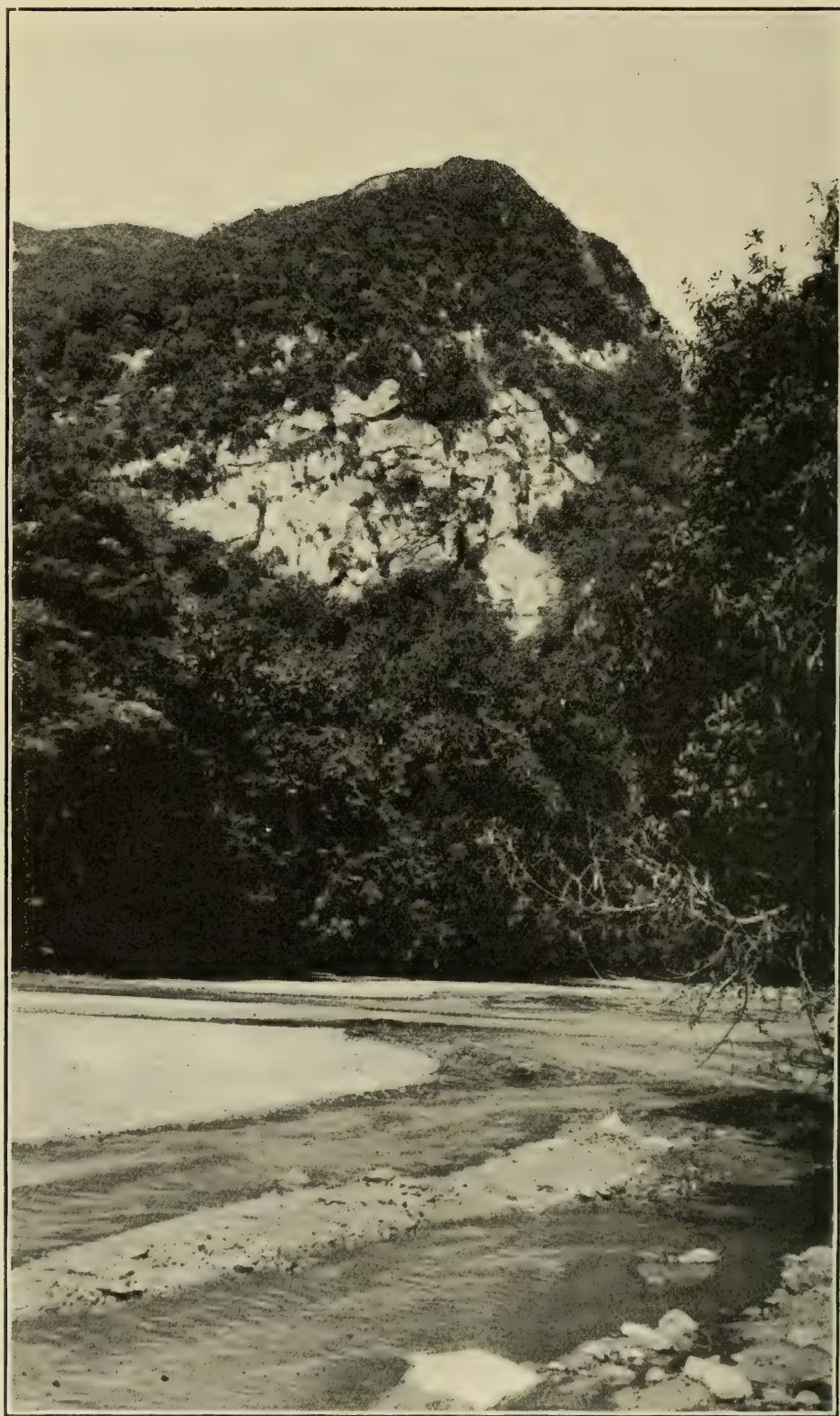


FIGURE 13.—*Machareti Formation*

As seen in the eastern part of the gorge of Río Charagua, in the Sierra de Charagua.

to the late diastrophism which gave rise to the erosion of the modern topographic features."

Machareti formation.—The strata above the fluvio-glacial grits and conglomerates of the Mandiyuti formation and below the chert and limestone which overlie the Bermejo series, as here defined, are named the Machareti formation. The type locality is in the gorge of Vitiacua creek a few miles west of the town of Machareti. The formation is at most places about 1,000 feet in thickness, but varies from slightly less than 800 to a little more than 1,600 feet.

These beds are mostly sandstones, but include also a considerable amount of shale and clay. The sandstones are massive, irregularly bedded and coarsely laminated. Their effect on the topography may be seen in figure 13. They display various tints, from light yellowish brown or cream to deep red or maroon. In places they are white and have a sugary texture. Ordinarily the interbedded shales and clay are red; the shales are non-fissile.

VITIACUA LIMESTONE AND CHERT

This formation has been observed in the north part of the Sierra de Aguarague, and its probable equivalent has been mapped in two localities in the north part of the Sierra de Charagua. Float derived from it was seen in the Sierra de Mandiyuti and elsewhere, but it was not observed in place in that range or in other localities where detailed work was done.

The type locality is in the western part of the gorge through which Rio Vitiacua traverses the Sierra de Aguarague, about a mile downstream from the portals through the hogbacks which form the western slopes of the range. At this exposure the Vitiacua formation consists of thin beds of chert and cherty limestone separated by thin partings of clay. Some of the chert is purplish pink and is massive or in extensive sheets averaging 2 inches in thickness. The rest is brown or white and occurs in irregular nodules or concretions scattered through the thin calcareous strata. The entire formation at this locality is only a little over 15 feet in thickness.

In the north part of the Sierra de Charagua, $2\frac{1}{4}$ miles due west from the village of Tacuru, several beds of coarsely crystalline, light gray limestone are exposed in the gorge of Tacuru Creek. The limestone is 6 feet thick and is more resistant than the underlying sandstones or overlying shales. It contains no chert at this place, but scattered among the calcite crystals are numerous grains of white quartz, well rounded and washed entirely clean of clay particles. In a similar stratigraphic position near the western end of the Saipuru gorge, a few miles farther south, in the



FIGURE 14.—West Portal to Gorge cut by the Rio Charagua through the Sierra de Charagua

The view is taken looking south across the sandy beds of the Rio Charagua. The resistant Tacuru sandstone rises steeply at the left to form the westernmost hogback along the flanks of the range; the softer Tatarenda shales for the gentle hills at the right.

Sierra de Charagua, there are several massive beds of variegated calcareous sandstone. In some of these beds the grains of sand are not in contact with each other, but are merely thickly scattered through the calcareous rock. These two formations are believed to be equivalent to each other and to the cherty limestone at the type locality of the Vitiacua formation, although this correlation is by no means a sure one.

Wherever observed, the Vitiacua limestone and chert is structurally conformable with the underlying beds of the Bermejo series and with the overlying Tacuru formation. There is, however, an important stratigraphic break between the Bermejo and Tacuru formations, as indicated by conglomerates in the latter, which are formed of pebbles and talus fragments derived from the former. The limestone and chert at the type locality in the Vitiacua gorge is the same formation as that to which Steinmann has applied the name "Horizonte Calcareo - dolomitico." Al-

though Steinmann described this formation as Cretaceous on the evidence of fossils which he found within it, the more extensive collections recently described by Bonarelli, to which reference has been made in a preceding paragraph, indicate that it is to be correlated with the European Lias and should therefore be considered as Late Triassic or Early Jurassic. The hiatus is, therefore, presumably due to an erosion interval subsequent to the deposition of the Vitiacua beds and preceding the accumulation of the Tacuru sediments.

It is believed that the Vitiacua limestone and chert is the equivalent of the Cajones limestone of the Sierra de Santa Cruz,¹¹ but because of the impossibility of definitely verifying this tentative working hypothesis it is deemed wise to use separate names for the two similar zones in the two widely separated localities.

TACURU FORMATION

Resistant sandstones overlie the Vitiacua sandstone and chert, or the Bermejo series where that thin formation is wanting, and form the sharp crested, steeply inclined hogbacks which border the mountain ranges, at least on their western slopes, and are present in the western portion of each group of *cuestas* (see figure 14). They have been observed in all parts of the region under discussion. The type locality is the eastern part of the Tacuru gorge, in the Sierra de Charagua. The formation may be defined as including all the beds between the "portals," one mile west of the village of Tacuru, and the outcrop of the Vitiacua (?) limestone, $1\frac{1}{4}$ miles farther upstream.

The Tacuru formation is a variable series of sandstone and sandy shales with a small amount of clay shale recurring at irregular intervals throughout its various members. The sandstones are commonly light gray or even white, but include also a considerable amount of red beds. The beds are generally quite irregular; many of them are strongly cross-bedded. Some appear to be eolian deposits; the rest are presumably fluvial and possibly lacustrine sediments. The shales are commonly mottled or variegated with numerous tints of maroon, carmen, or purplish gray, but in places they display a brown monotone. All of them are non-fissile and many are in reality thick beds of uncemented but closely compacted clay.

This formation is generally between 3,000 and 4,000 feet in thickness, but at the type locality it is probably somewhat greater than 4,000 feet, and in certain other places its thickness is only about 2,000 feet.

In the northern part of the Sierra de Charagua the lower 200 feet of the Tacuru formation is thin-bedded clay shale, yellow brown to deep red,

¹¹ Heald and Mather, 1922, pp. 565-567.



FIGURE 15.—*Upper Sandstone Member of the Tacuru Formation*
View taken at the east entrance of the gorge of Rio Charagua, in the Sierra de Charagua.

with occasional streaks or splotches of greenish gray. This is overlain by massive light-colored sandstones in beds of varying thickness, many of which are between 2 and 10 feet thick. For the most part, these strata are comparatively soft and crumbling.

Between 600 and 900 feet above the base of the formation, there is a sandstone member of great resistance to erosion. Its beds display varying tints of red alternating with white or light gray; some of them are separated by occasional partings of red clay. These strata are all very irregularly bedded and for the most part are composed of very small grains of quartz, which give a rather fine texture to the rock. Still higher in the stratigraphic sequence the sands become coarser and the beds more massive, so that in the middle of the formation, 1,800 to 2,200 feet above its base, the sandstones are of great thickness and show much cross-bedding and many irregular laminations, as though deposited by shifting deltaic currents. This portion of the formation is grayish white. Above these beds the strata are comparatively soft and not well exposed, but at the top of the formation there are 200 to 300 feet of very resistant white and gray quartzitic sandstones. These are composed of well rounded quartz grains firmly bound with siliceous cement. There is little or no mica nor feldspar associated with the quartz grains, which for the most part are very clean. Cross-bedding is noticeable, but not nearly so prominent as in the underlying beds. These resistant top strata of the Tacuru formation give rise to the conspicuous portals through which the streams leave the mountain gorge and debouch on the undulating lowland to the east.

This quartzitic upper member of the Tacuru formation forms the outermost hogbacks on either side of the Charagua range. Its influence on the topography is illustrated in figure 3, in which this resistant member of the Tacuru formation may be seen rising from the margin of the Chaco on the east side of the Sierra de Charagua, a short distance south of Saipuru. In figure 14, which shows the south side of the valley of Rio Charagua at the point where this river enters the Sierra de Charagua from the west, the top member of the Tacuru rises steeply to form the hogback partially visible at the left of the photograph. The slightly cross-laminated sands in this portion of the Tacuru formation are also shown in figure 15, a bluff rising from the banks of Rio Charagua at the eastern entrance to the Charagua gorge.

In the Cuestas de Oquita the Tacuru formation is about 3,500 to 4,000 feet in thickness. The exact contact between it and the underlying strata was not observed, nor was the Vitiacua limestone noted in those hills through which a cross-section was run along the channel of Rio Parapiti.

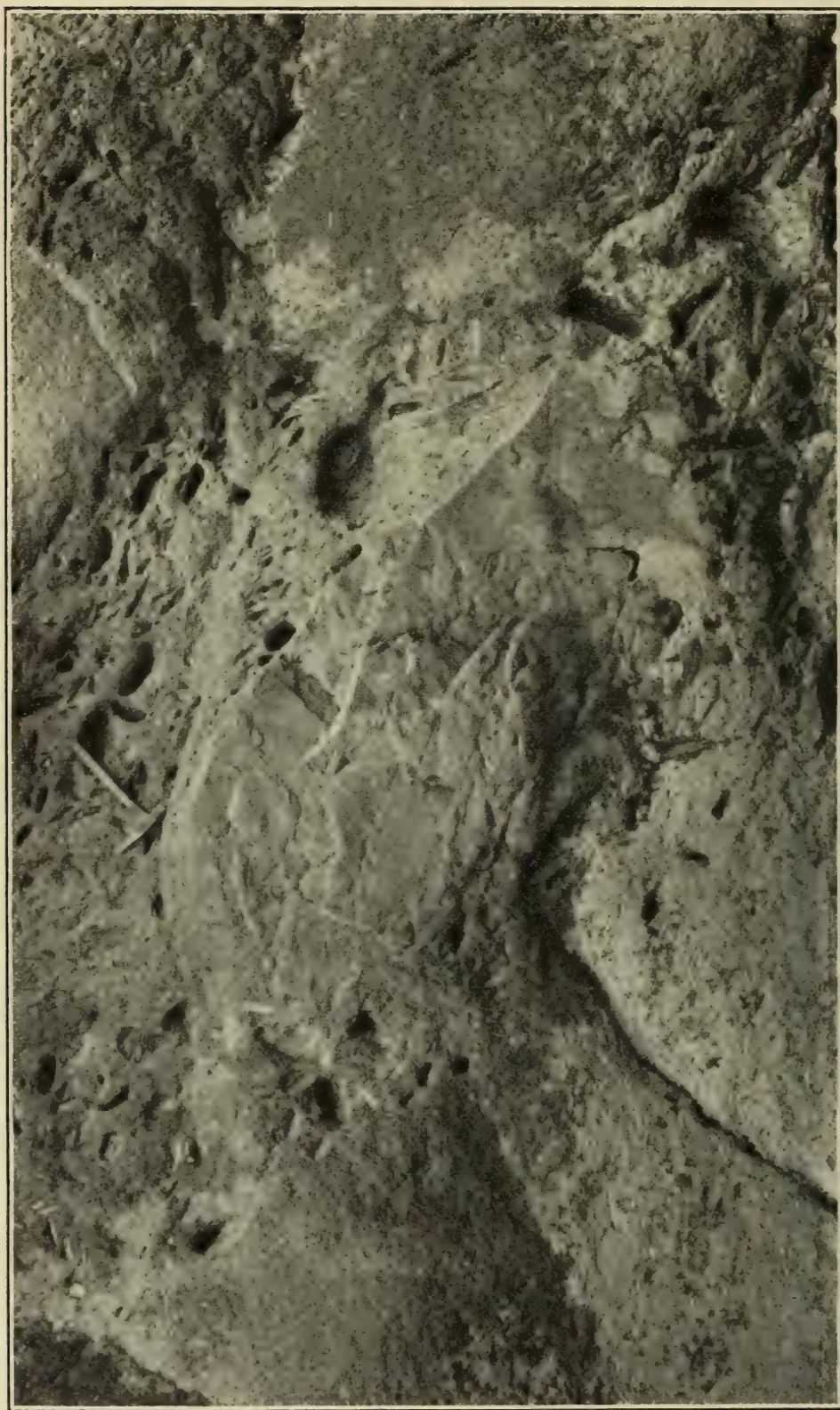


FIGURE 16.—Conglomerate in the basal part of the Tacuru Formation
This exposure is in the Quebrada de Los Monos, Sierra de Aguaraque.

The lower strata of the Tacuru, as observed in that section, are red and white sandstones which alternate irregularly in the stratigraphic succession. Above these the sandstones are cross-bedded and are brown or gray. Near the top of the formation the sands are soft, crumbly, cross-bedded, and chocolate brown or maroon. The intervening shales are not well exposed, but are in general brown or some shade of red; they are, of course, non-fissile. The uppermost member of the formation is a very resistant gray-white sandstone which forms the western line of hogbacks along the margin of the *cuestas*.

The Tacuru formation underlies the gently sloping hogbacks in the western half of the Mandiyuti range. About 2,000 feet of strata belonging to this formation are there exposed and its top was not seen in that locality. As elsewhere, there are cross-bedded sandstones with considerable amounts of interstratified shale. Yellow and white are the predominating colors of these rocks, but in some places the weathered surfaces are a brilliant vermilion or some other shade of red. Immediately east of the Mandiyuti fault, which crosses Rio Cuevo 3 miles west of the village of Cuevo, at the eastern front of the Mandiyuti range, there are several beds of light gray sandstone which outcrop along the channel of the river. These are separated from the Bermejo beds immediately upstream by the major fault, to be described in a subsequent paragraph, and are probably the uppermost beds of the Tacuru formation.

Farther south in the Sierra de Aguarague the Tacuru formation appears to be thinner than in the more northern localities, as measurements made in that range indicate its thickness to be between 1,800 and 2,200 feet. The amount of shale in the stratigraphic sequence is also very much reduced. Thus the formation in this mountain range is chiefly sandstone, light gray or white, occurring in massive resistant beds, some of which are as much as a hundred feet thick. Between some of these sandstone beds there are small amounts of soft crumbly sands and clays.

In the Quebrada de Los Monos an unusual and very significant feature was noted near the base of this formation. Just before reaching the point at which farther progress upstream on muleback is barred by huge boulders entirely blocking the stream channel, there is an outcrop of a thirty-foot conglomerate which is believed to represent the base of the Tacuru formation at this locality in the Sierra de Aguarague. The matrix of this conglomerate is fine red sand. The pebbles are of three kinds. Some are small subangular fragments of quartz, quartzite, and chert a quarter to a half inch in diameter. Others consist of subangular slabs and chunks of red Bermejo sandstone and sandy shale 2 to 6 inches in length. These are irregularly distributed throughout the conglomerate without any

notable parallelism. They are the softest part of the rock and consequently on weathering these slabs form pits and cavities such as those on a level with the hammer in the upper part of the exposure shown in figure 16. The third type of pebble is illustrated by the large mass of Bermejo sandstone, 5 feet or more in length, in the center of this same photograph. This member of the Tacuru formation is thus composed in large degree of material derived from the erosion of the Bermejo shales. Presumably it was deposited by torrential streams in alluvial cones or on an alluvial plain. It is, therefore, indicative of an unconformity between the Bermejo and Tacuru formations, although, so far as known, these beds are all structurally conformable with each other.

No fossils were found within the Tacuru formation, and it is therefore impossible to state its age with any definiteness. There is little doubt but that the stratigraphic break indicated by the presence of eroded Bermejo fragments in the Tacuru formation occurs above the Vitiacua limestone, although this limestone is not present between the Bermejo and Tacuru beds in the locality at which the conglomerate was observed. Accepting Bonarelli's reference of the Vitiacua limestone and chert to the late Triassic or early Jurassic period, it would appear likely that the Tacuru formation is of late Mesozoic age. Unfortunately, the fossils found in the overlying Tatarenda beds to which reference will be made in a subsequent paragraph are by no means diagnostic, so that it is not possible to place an upper time limit on the age of the Tacuru. It is improbable, however, that this formation could be younger than early Tertiary.

The Tacuru formation as thus defined is evidently the equivalent of Bonarelli's "*Areniscas superiores*," to which a Cretaceous age has been assigned.¹² The only fossils to which Dr. Bonarelli makes reference are undescribed reptilian bones which he considers as in agreement with this assigned age.

TATARENDA FORMATION

Overlying the resistant "hogback-maker" sandstone at the top of the Tacuru formation there is a thick series of soft sandstones, shales, unconsolidated sands, and clays to which the name Tatarenda formation is here applied. These strata have in general been removed from above the older beds in the sierras and cuestras; they are present only beneath the lowland areas and along the outer flanks of the uplands. The type locality is the broad valley between the Sierra de Limon and Sierra de Charagua, in which the little Indian village of Tatarenda is situated.

The Tatarenda beds are characterized by their lack of resistance to

¹² Bonarelli, 1921. pp. 77-78.

erosion, in which regard they are in strong contrast to the strata composing the Tacuru formation and Bermejo series. Sandstones are poorly cemented, soft, and crumbly; shales are for the most part easily friable and indistinctly laminated; many of the beds are in reality unconsolidated clay, marl, or sand. Occasionally there are beds of harder rock, well cemented sandstones or compact shales, but these are rare. Typically the Tatarenda beds are light chocolate brown, but in places the sandstones are white and sugary in appearance. Elsewhere the sands may be maroon, carmen, or other shades of red. Likewise the shales at many places depart from the common brown tint and display brilliant hues of red, purple, or green.

It is not possible to state the maximum thickness of the Tatarenda formation with accuracy because its upper beds are everywhere concealed beneath the veneer of Quaternary deposits which lap up against the lower slopes of the mountains and are widespread over the surface of the lowlands. Doubtless, too, there is considerable variation in thickness from place to place, for it is evidently a deposit made in large part by streams debouching into lakes or shallow seas or spreading their debris across low-lying lands. Along the eastern front of the Sierra de Charagua this formation has a minimum thickness of slightly over 3,000 feet.

Beds of this formation aggregating more than 3,000 feet in thickness outcrop along the channel of Rio Saipuru west of the Sierra de Charagua and are traversed by that stream before it passes through the portal between the hogbacks formed by the resistant top beds of the Tacuru formation. In that locality the lower 2,000 feet of the Tatarenda formation consist of light chocolate brown and maroon clay shales and cross-bedded sandstones, irregularly alternating with each other. These beds are for the most part very poorly consolidated, soft and crumbly. The sands contain numerous partings of clay which separate beds of varying thickness, some of which are as much as 20 feet thick. Irregular masses of clay also occur as inclusions within the sandy beds. About 2,000 feet above the base of this formation there is a member consisting of thin-bedded micaceous sandstone and shale, rather well cemented into firm rock by calcareous cement and aggregating 200 feet in thickness. Where Rio Saipuru crosses this member its beds are steeply inclined toward the west and flexed into strongly pitching anticlines and synclines, as shown in figure 17. Certain of the calcareous beds are crowded with the shells of a species of pelecypod and are so thickly strewn with the tiny valves of an ostracod as to appear oolitic. Above these marine fossiliferous strata the beds resemble closely those in the lower part of the formation. The materials composing them are poorly sorted, some of the strata contain-

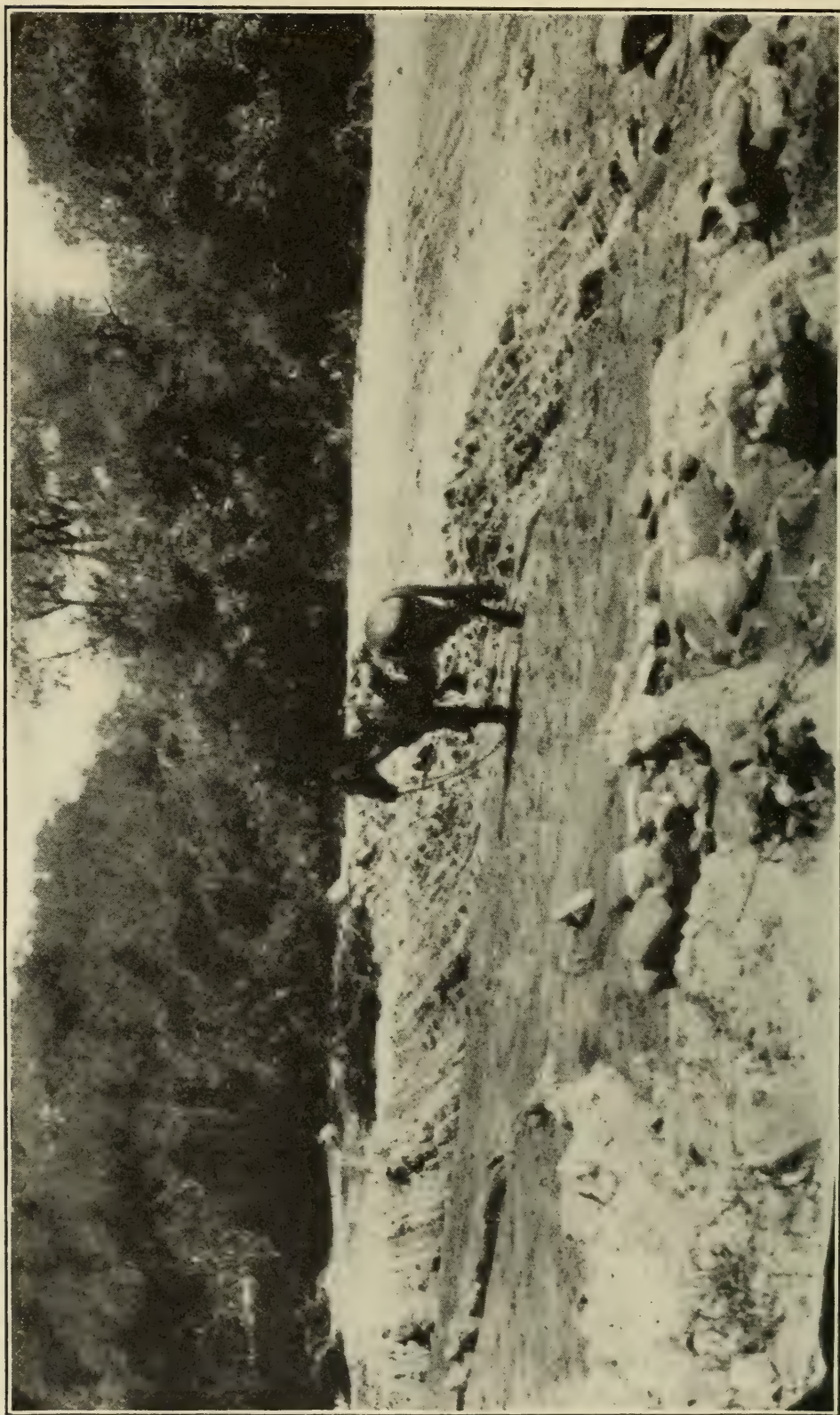


FIGURE 17.—*Steeply inclined, fossiliferous beds of the Tatarenda formation*
This exposure is in the channel of Rio Saipuru, on the west side of the Sierra de Charagua.

ing considerable coarse, gritty materials heterogeneously intermingled with fine sand and masses of clay. As in the lower beds, the cement which binds the sand particles together is quite inadequate to make a firm rock and the strata weather readily.

The outermost series of low hogbacks along the flanks of the Sierra de Aguarague and the adjacent lowland areas on either side the range are overlain by soft crumbly beds of the Tatarenda formation. A total thickness of upward of 4,000 feet was measured at one locality. Ordinarily, about a thousand feet of Tatarenda strata are present in the low hogbacks. Interspersed through the basal portion of the formation, there are several conglomeratic horizons. These contain subangular fragments of sandstone and other rocks derived from the Bermejo-Tacuru series. In the Quebrada de Los Monos, for example, these conglomerates are well displayed in the last series of portals through which the stream passes after it turns eastward from the center of the range. The conglomerates at that locality are very evidently the result of torrential accumulation. A short distance upstream from these outer portals in the Quebrada de Los Monos, there is a cherty sandstone composed of beds which range up to 2 feet in thickness, containing an abundance of nodules and sheets of brown chert, as well as a large amount of calcite in large crystals filling cavities in the sandstone. This calcite-chert horizon is two or three thousand feet above the Vitiacua formation as observed in the gorge of Vitiacua creek and, as pointed out by Bonarelli (1921, page 78), it is quite distinct from the beds which Steinmann has called the "Horizonte Calcareo-dolomitico."

Although, so far as known, the Tatarenda formation is structurally conformable with the underlying Tacuru formation, the presence of a stratigraphic break between the two formations is indicated by the composition of the conglomerates near the base of the Tatarenda. Presumably the episode of sedimentation responsible for the Tacuru formation was closed by crustal warping which elevated a part of the region occupied by the Bermejo-Tacuru series and formed uplands whence came the debris of which the Tatarenda beds are composed. Much of the accumulation was of a torrential nature, but in many localities only the finer sediments were washed broadcast over lowlying plains or into shallow seas. The red and brown colors so commonly observed in this formation are chiefly due to the fact that much of the Tatarenda sediments was derived from erosion of the Bermejo red beds.

This formation is approximately the equivalent of Bonarelli's "Terciario Subandino" series, which that geologist appears to have referred to the Tertiary period on the basis of its lithology. Unfortunately, the

fossils collected from the beds traversed by Rio Saipuru and above referred to are not diagnostic of the age of the inclosing strata. The collection was submitted to the specialists of the United States Geological Survey for identification. Dr. David White, in commenting on them, states that "according to E. O. Ulrich, the numerous ostracods appear to belong to a single species of *Bythocypris*. Some of the pelecypod casts suggest *Tellina*, but are not well enough preserved for positive identification. Both the ostracods and pelecypods are simple, long-lived types that are of little use in age determination." E. O. Ulrich, in Eastman's translation of Zittel's *Paleontology*, characterized *Bythocypris* as "typically recent, but a number of Paleozoic forms have also been assigned to this genus." Dr. W. H. Dall, in the same textbook, gives the age limits of *Tellina* as Jurassic to Recent. The fossils, therefore, are in harmony with the lithologic suggestion that the inclosing beds are of Cenozoic age. In all probability the Tatarenda formation will prove to be Tertiary.

Identical pelecypod remains were found in similar strata north of Rio Grande, 3 miles northwest of Abapo. Doubtless these were from the beds in which fossil shells were observed by Romanes, Madgwick, and Witteveen, as reported by Bonarelli (1921, page 79).

QUATERNARY DEPOSITS

Both the Chaco plain and the intermontane lowlands are quite generally covered with recent deposits of unconsolidated gravel, sand, silt, and clay, which rest unconformably on the eroded surface of the Tatarenda and older beds. These are in part eolian, in part fluvial, and probably in part lacustrine in origin.

Within the mountains the hillsides are ordinarily so steep that only slight accumulations of such material are present. They rarely offer a serious handicap to the work of the geologist in deciphering the nature and structure of the older beds. The thickness of these surface materials beneath the lowlands is, of course, very variable. The underlying strata are almost everywhere concealed in the flat regions, and the Quaternary deposits probably attain a thickness of two or three hundred feet at many places.

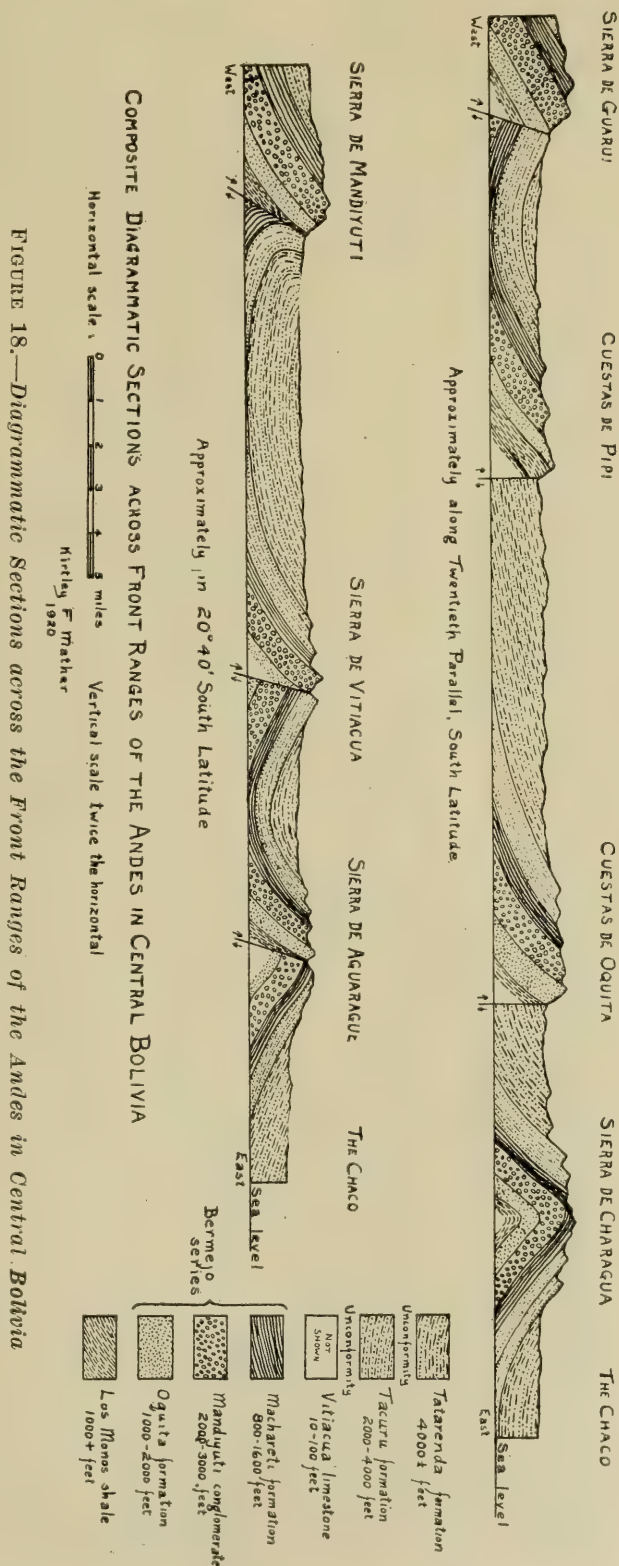
GEOLOGIC STRUCTURE

GENERAL STATEMENT

Structurally, the area under consideration consists of a series of closely compressed anticlines extending for long distances north and south and separated by comparatively broad synclinal troughs, some of which are

modified by the presence of tilted fault blocks whose longer axes are parallel to the trend of the anticlines. Each of the mountain ranges, or sierras, which have been described above is a long, narrow, sharply folded anticline. The length of these folds is in each case approximately equivalent to the length of the sierra and is, therefore, to be measured in scores of miles. The width of each fold is considerably greater than the width of the mountain range for which it is responsible and varies between 5 and 15 miles.

The strata forming the limbs of the anticline are tilted at angles of 25 degrees to 75 degrees, or even more; their average slope is about 40 degrees. Strictly speaking, each anticline is doubly plunging, for each dies out at either end, but the length of the folds is so great that their crests are practically horizontal for great distances. Their axial planes are seldom vertical, but more or less toward the east, suggesting that the great thrust which crumpled the region came from the west. Each of the great anticlines, with the exception of the Charagua anticline, is sheared along a major fault-plane which trends parallel to the anti-



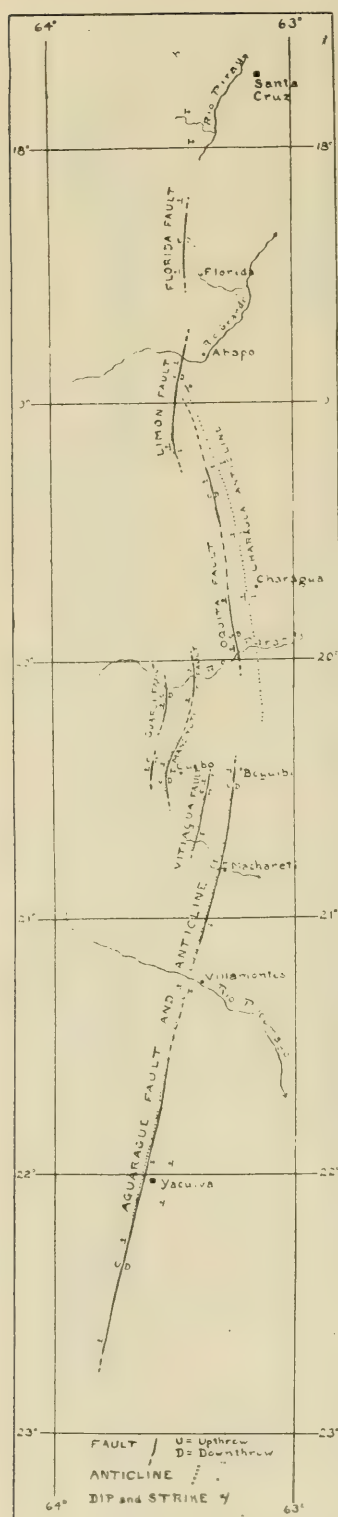


FIGURE 19.—*Tectonic Map of the Area shown in Figure 1*

cline and is situated a short distance east of the crest of each fold (see figures 18 and 19). These faults are thrusts with the overhanging wall on the west and with the fault-plane inclined at a high angle from the horizon. Displacement along each fault-plane ranges from 3,000 to 10,000 feet, or even more. In many places the fault movement is more significant than the fold, but elsewhere the fold is the more prominent of the two.

With the possible exception of the Cuestas de Ipahuazo, the structure of which has not been satisfactorily determined, each of the cuestas, or groups of hogback hills, described above is a tilted fault-block with monoclinial dip toward the west. These blocks are scores of miles in length from north to south and have a width from east to west of 5 to 15 miles. Each is terminated on the east by a major fault-plane, vertical or nearly so, with the upthrow side on the west, along which the displacement amounts to several thousand feet. The strata of which these fault-blocks are composed dip toward the west at angles varying between 20 degrees and 70 degrees or even more. In general, the dip is greatest at the east margin of the block, where, indeed, the strata are sometimes vertical, and decreases in amount toward the west.

Each of the intermontane lowlands is a comparatively broad, shallow syncline which extends for scores of miles in a north-south direction and is between 5 and 20 miles in width. On either side of the trough the strata rise with increasing dip until they merge into the flanks of the adjacent anticline or the westward portion of the adjacent monocline. Beneath the western margin of the Chaco plains the strata dip downward toward the east at angles which decrease with distance from the mountain front. Apparently, the Chaco is structurally an ex-

tremely broad, shallow synclinal trough comparable to the Big Horn Basin.

FLORIDA FAULT

As observed from the trail passing through Palissa and Florida, the bold front of the Sierra de Florida appears to be a fault-scarp only slightly modified by erosion since movement took place along the fault-plane. The west side of the fault-plane is, of course, the upthrow side, and the displacement must amount to at least six or eight thousand feet. The Bermejo-Tacuru beds composing the sierra strike in a general north-south direction parallel to the trend of the fault-plane and display gentle dips toward the west away from the fault. Their dip, however, is not uniform, and many minor undulations both in degree and in direction are noted. One important anticlinal axis is roughly defined by the north-west dip of the strata in the hills immediately south of Mount Carobana and the southwest dip of the same beds in Mount Cuchilla and the hills south of it. The attitude of the beds adjacent to the fault on the downthrow side was not observed, nor is the hade of the fault-plane known. By analogy with the conditions observed far to the south, it may, however, be safely inferred that the Florida fault pitches steeply toward the west, and that the beds on its east side are dragged upward into almost vertical positions.

LIMON FAULT AND ANTICLINE

Although the general structure of the regions occupied by the Sierra de Limon, the piedmont lowland immediately to the east, and the Limon Valley is comparatively simple, and therefore easily determined, the details of structure are in places somewhat obscure and were not determined with accuracy. The steep escarpment along the east front of the Sierra de Limon is a fault-scarp. The fault is in all probability a thrust along a steeply inclined plane near the crest of a slightly overturned anticlinal fold. Displacement is measured in thousands of feet; the west side is the upthrow side. The mountains are in the main anticlinal; the Limon Valley is synclinal.

Three or four miles northwest of Abapo the exposed beds of Tatarenda shale strike north 42 degrees east and dip 80 degrees toward the south-east. These are evidently on the eastern limb of the faulted anticline. Three or four miles farther westward the beds in the upthrow block which form the mountains west of the fault-scarp appear to dip gently westward.

In the region, 6 to 8 miles south of Rio Grande, along the trail from

Abapo to Limon, the upper Tacuru and lower Tatarenda beds dip eastward at angles between 12 degrees and 42 degrees, with strike varying from north 10 degrees east to north 50 degrees west. The flexures at that locality seem to represent the northwest extension of the Charagua anticline or the dying out of the Oquita-Taimbermi fault.

Near Rincon the strata also dip toward the east; the Tatarenda formation, in the low hills near that hamlet, displays dips of 10 degrees to 12 degrees, while the Bermejo-Tacuru series, a half mile to the west, dips eastward at angles of 20 degrees to 30 degrees and forms hogbacks along

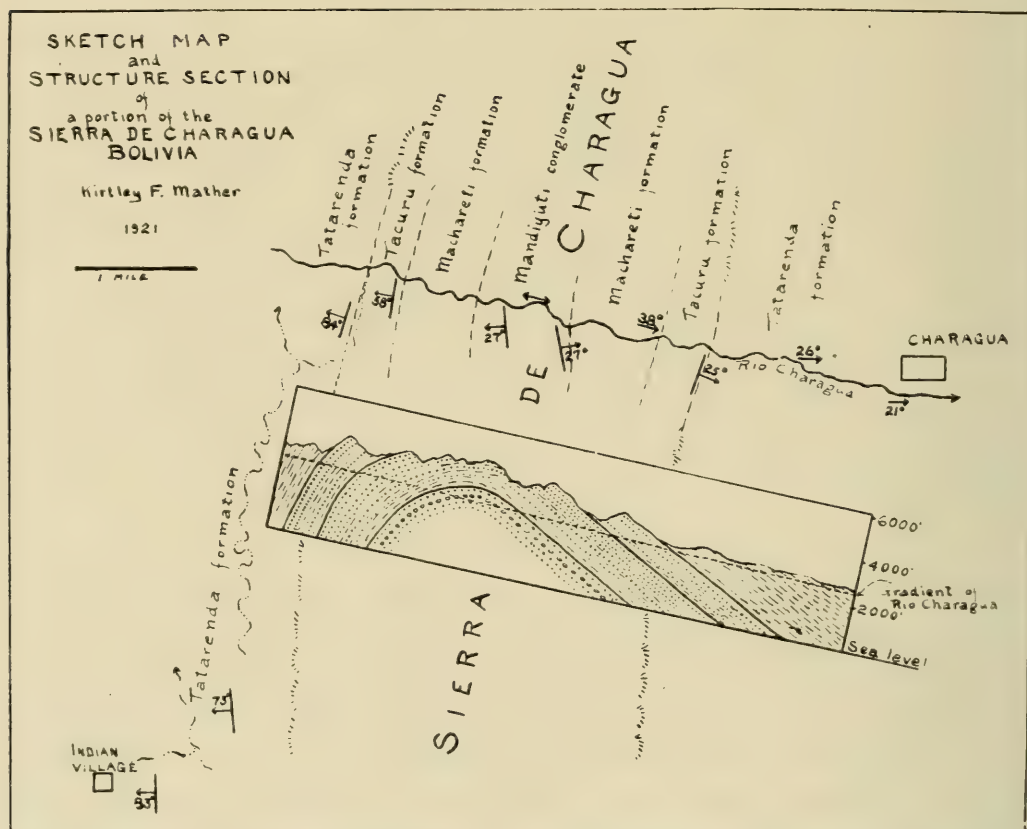


FIGURE 20.—Sketch Map and Structure Section of a Portion of the Sierra de Charagua, Bolivia

the eastern front of the sierra. Evidently the Limon fault decreases in magnitude toward the south and gives place at Rincon to an anticlinal fold with little breaking along its axial plane. At Tatarenda the sands and shales of the Tatarenda formation strike north 8 degrees east and dip eastward at an angle of 58 degrees.

CHARAGUA ANTICLINE

The Sierra de Charagua is structurally a long, narrow, strongly compressed, asymmetrical anticline. As shown in cross-section in figures 18

and 20, the strata dip westward on the west side of the range at angles varying from 40 degrees to 80 degrees, while on the east side of the range they dip eastward at angles of 20 degrees to 70 degrees. The crest of the anticline is approximately in the middle of the mountain range and extends in a broadly crescentic curve from a point 4 or 5 miles northeast of Limon to a point 10 or 12 miles northeast of Boyuibi, as indicated on the accompanying map, figure 19. The fold is more than 85 miles in length and is about 10 miles wide. It is apparently not connected with any other structural feature, but is roughly parallel to similar folds situated several miles to the westward.

Along the crest of the Charagua anticline the rocks appear to be much broken, but no faults of any great significance were observed. The exposure of the Espejos formation in the gorge of Rio Tacuru is due to a fault, the exact nature of which could not be ascertained from the one exposure. It is probably a thrust-fault, which complicates the western limb of the anticline at that locality.

OQUITA-TAIMBERMI FAULT

The geologic structure of the Cuestas de Oquita and their northward extension in the Cuestas de Taimbermi is typical "Great Basin" structure. The steep escarpment along the eastern margin defines a major fault trending in a general north-south direction roughly parallel to the Charagua anticline. At the point where Rio Parapiti crosses this fault its plane is vertical, and it is probable that throughout its extent the fault-plane does not depart far from verticality. The western side is the upthrow side and the movement along the fault-plane amounts to about 10,000 feet.

At the locality just mentioned on the north bank of Rio Parapiti, a photograph of which forms figure 21, the fault has resulted in the formation of a sheer zone a hundred feet or so in width, within which the beds are greatly shattered and the prevailing dip is vertical. This is true of the Tatarenda shales on the margin of the downthrow block east of the fault-plane, as well as of the Oquita sandstones on the upthrow side. A few rods farther west the strata are inclined westward at an angle of 85 degrees, and for nearly a mile west of the fault-plane the dip is 80 degrees or higher. Beyond that point the dip gradually lessens, until at the western margin of the group of hills, $2\frac{3}{4}$ miles west of the fault-plane, the top beds of the Tacuru formation are inclined westward at an angle of only 14 degrees. This dip continues westward, as indicated by the attitude of the Tatarenda strata, for several miles. Throughout the entire group of the Oquita Hills the strike of the beds is within a few

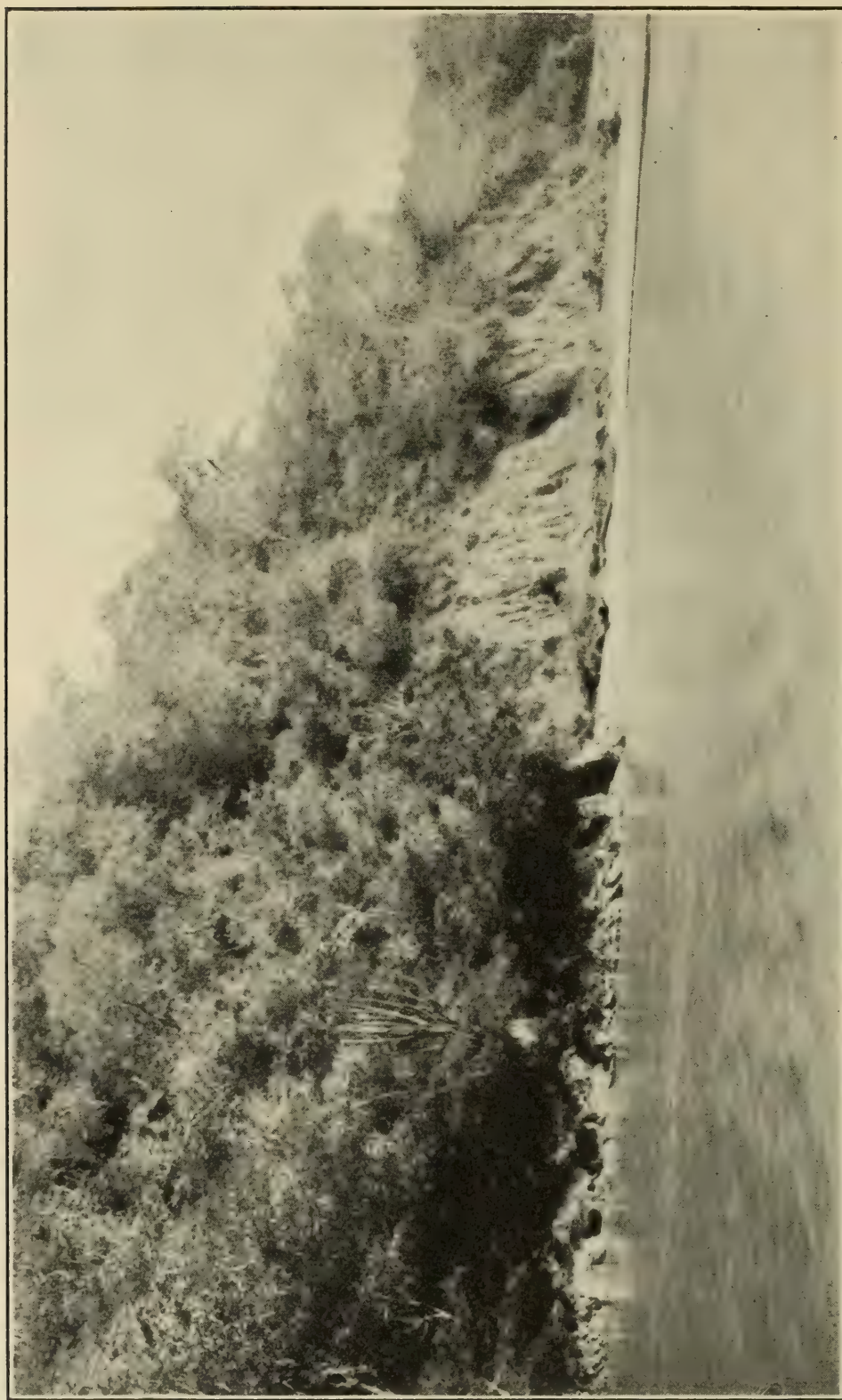


FIGURE 21.—*North Bank of Rio Parapiti*

This view is taken at the point where it crosses the Oquita fault. The resistant rocks in the shadows in the left half of the view are approximately vertical sandstones of the lower Bernejo or Upper Devonian series, on the upthrow side of the vertical fault-plane; in the right half of the view the nearly vertical beds in the sunlight are of the Tatarenda formation, on the downthrow side of the fault.

degrees of north, but farther to the north, in the hills west of Taimbermi, the strike swings westward, so that it varies between north 20 degrees west and north 30 degrees west.

MANDIYUTI FAULT AND ANTICLINE

The Mandiyuti fault presents a sigmoid plan and is known to extend from the vicinity of Pipi southward more than 30 miles, passing 3 or 3½ miles west of Cuebo. At the north it forms the eastern margin of the tilted fault-block responsible for the Cuestas de Pipi. The structure of these hills is quite similar to that of the Cuestas de Oquita. The fault-plane along the east front is nearly vertical; displacement was more than 10,000 feet. As elsewhere, the west side is the upthrow side. Immediately west of the fault zone in the Parapiti Canyon the lower beds of the Bermejo series dip westward at the comparatively low angle of 23 degrees. The inclination steepens farther to the west, so that a half mile from the fault the beds are tilted at an angle of 54 degrees, the steepest dip observed within this group of hills. Still farther westward the dip becomes more gentle, and midway of the width of the cuestas the inclination is 27 degrees toward the west. This dip remains fairly constant throughout the western half of the series of ridges and presumably continues beneath the Guarui Valley.

Ten miles south of Wirandi the Mandiyuti fault has much less displacement, so that only the uppermost beds of the Tacuru formation are brought above drainage by it. Still farther southward the fault-plane curves strongly toward the west and the displacement increases, so that all of the Bermejo-Tacuru series is exposed in the Sierra de Mandiyuti. Where crossed by Rio Cuebo, the fault-plane is inclined at an angle of about 60 degrees toward the west and the displacement is at least 10,000 feet. The hanging wall on the west is the upthrow side and the fault is, therefore, a thrust. East of the fault-plane the topmost beds of the Tacuru formation are overturned, so that they dip at an angle of 74 degrees toward the west in close proximity to the fault zone. A few hundred yards to the east the strata are vertical, and beyond that they dip at successively lower angles toward the east. West of the fault-plane the strata dip westward at angles varying between 40 degrees and 45 degrees, the inclination toward the west becoming more gentle farther from the fault-plane, until at the western margin of the range the dip is only 10 degrees. The Mandiyuti range is, therefore, a tilted fault-block which has been pushed bodily eastward and overrides the shattered and bent strata along the western margin of the Cuebo lowland.

GUARUI FAULT

The eastern front of the Sierra de Guarui is the topographical expression of the Guarui fault, a crustal feature closely similar to the Mandiyuti fault and situated 6 to 8 miles farther westward. The fault trace was mapped for only about 10 miles southward from the point where it crosses Rio Parapiti. In that portion of its extent it curves gently, so that it is convex toward the east. The western side is, as usual, the upthrow side; the displacement is approximately 10,000 feet. Presumably the fault-plane is inclined westward, like the Mandiyuti fault-plane, but the details of its structure were not ascertained.

Ten miles south of Rio Parapiti the fault-plane is projected into a group of irregular hills which seem to bridge the space between the western outposts of the Sierra de Mandiyuti and the eastern front of the Sierra de Guarui. Here the structure is rather complex, although in general it appears to be an anticlinal fold which is apparently the southern extension of the Guarui fault.

CHIRETI FAULT

The fault escarpment which forms the eastern front of the Sierra de Chireti and rises boldly above the western outposts of the Sierra de Mandiyuti, 7 miles west of Cuebo, is directly in line with the southward extension of the Guarui fault. The intervening area was not surveyed, and it may be that the Chireti fault is actually the southern continuation of the Guarui fault. In any event, the Sierra de Chireti is a huge block of the earth's crust tilted downward toward the west and elevated along its eastern margin by this fault movement. Apparently, the fault-plane is approximately vertical. The beds immediately east of it dip gently toward the west, and hence there is no suggestion of an anticlinal fold at the place where these observations were made.

VITIACUA FAULT AND ANTICLINE

The Vitiacua fault begins close to Ibo and is delineated by the eastern face of the series of low westward-dipping *cuestas* which are the northern outposts of the Sierra de Vitiacua. These increase in height toward the south, in response to increased displacement along the vertical fault-plane. For several miles the break is a simple one, not complicated by folding, except that involved in the tilting of the upthrow block, but near Cangapi the fault becomes a sheared anticlinal fold. East of the fault-plane there appears a series of hogback foothills, formed of the eastward-dipping strata on the east limb of the broken arch. These increase in

height southward toward Rio Vitiacua. Where crossed by that river, these hogbacks reach more than half way to the crest of the range; the fault displacement appears to have decreased as the folding of the strata increased.

AGUARAGUE FAULT AND ANTICLINE

The beds forming the Sierra de Aguarague are crumpled and broken into a long, narrow, sharply compressed, anticlinal fold, sheared throughout four-fifths of its length by a thrust-fault. In places the fault displacement is the more important structural feature and gives rise to the prominent fault-scarp which forms the east front of the range at its northern end near Boyuibi and throughout the greater part of its length south of Yacuiva. Elsewhere, however, the fold is the dominant structure; the fault is of minor importance, and in places is almost, if not entirely, wanting. Thus, between Machareti and Yacuiva the eastern slopes of the range, as well as the western, are dip slopes, and the fault-scarp, if present, is near the middle of the sierra instead of along its eastern front.

Near the northern end of the range the geologic structure is well displayed in the gorge of Rio Vitiacua. There the thrust-fault is nearly as far from the eastern series of hogbacks along the outer slopes of the range as it is from the western ones. The western limb of the faulted anticline dips westward at angles which increase from about 20 degrees on the western margin of the range to more than 60 degrees midway the length of the canyon. The eastern flank of the anticline inclines toward the east at angles which vary between 7 degrees and 45 degrees. The thrust fault-plane is inclined toward the west at an unknown but probably rather steep angle. On either side of it there is a zone of shattered and contorted strata. The easily flexed beds of Los Monos shale in this shattered zone are intricately folded and crumpled, so that their dip varies much in degree and direction. The western side of the fault-plane is the up-throw side and forms the hanging wall. Displacement along the plane must have amounted to several hundred feet.

From Rio Vitiacua southward to a point a few miles southwest of Tarairi the thrust-fault retains about the same relative position with respect to the east front of the Sierra de Aguarague as that indicated in the Vitiacua Canyon. West and northwest from Tarairi the east front of the mountains is a remarkably regular and unbroken slope, inclined at an angle of about 25 degrees toward the east. As viewed from the trail east of the mountains, it appears likely that the fault is a major structural feature immediately west of this dip slope along the middle

of the range throughout this portion of its extent. A few miles farther southward, in the vicinity of Villamontes, the topography indicates that displacement along the fault-plane is less and less, until near Rio Pilcomayo it dwindles practically to nothing.

Detailed examinations of the structure of this range were also made in the Quebrada de Los Monos. At this locality the Sierra de Aguarague appears to be a simple anticline, little modified or entirely unmodified by faulting. On the east flanks of this anticline the strata dip eastward at angles between 40 degrees and 56 degrees. Near the crest of the fold, on its west limb, the shales of the Los Monos formation dip toward the west at angles between 50 degrees and 80 degrees. No certain indication of faulting was observed at this locality, although it is entirely possible that some breaking and slipping of the strata have taken place here. The ridge on the west side of the Los Monos Valley, where it trends northward along the crest of the anticline, is higher than that on the east side of the same valley, and there may be a fault parallel to the longer axis of the anticline between these two valley walls, in a similar position to that in the gorge of Rio Vitiacua, 30 miles to the north. If so, the west side is the upthrow side and the displacement could be only about two or three hundred feet.

Southward from Villamontes for many miles the trail swings far out among the forest-clad knolls and low hills of the plain, so that it is impossible to get a good view of the mountains from it. Almost nothing is known, therefore, concerning the appearance of the Sierra de Aguarague west and northwest of Soto. West of Yahuacua the range displays an uneven, but roughly horizontal crest, formed by westward-dipping sandstones which overlook a magnificent fault-scarp 1,500 feet in height. Along the fault trace is a discontinuous depression parallel to the major axis of the range. This is bordered on the east by hogbacks with strata inclined steeply toward the east. The structural conditions in this part of the sierra are therefore roughly similar to those in the vicinity of Rio Vitiacua.

Farther southward, between the latitude of Caiza and that of Yacuiva, the Sierra de Aguarague is appreciably lower. Its slopes are heavily wooded and there are no bold cliffs formed either by erosion along a fault-plane or by the slopes of transverse canyons. Apparently in this portion of its length the Aguarague fault is again becoming the dominant structural feature. Its position is nearer the eastern front of the range and the east-sloping *cuestas* dwindle to disappearance. South of Yacuiva, in the Argentine, the eastern front of the range is almost everywhere a fault-scarp varying between 1,500 and 1,000 feet in height.

West of Aguaray the crest of the Sierra de Aguarague is only about a thousand feet above the bordering lowlands. Its eastern front rises boldly in a steep fault-scarp which overlooks the plain. At this place the fault-plane has a hade of about 25 degrees and pitches toward the west. The strata on its upthrow side dip about 10 degrees toward the west and strike north 25 degrees east, approximately parallel to the trend of the mountain range and the strike of the fault-plane. From this point southward the structure of the Sierra de Aguarague is better described as a tilted fault-block than as a faulted anticline, so inconspicuous is the folding in comparison with the faulting. Ten miles south of Tartagal the displacement along the Aguarague fault decreases rapidly and a mile or two farther southward it becomes so slight that none of the resistant beds of the Tacuru formation are lifted by it above the level of the plain.

GEOLOGIC HISTORY

DEVONIAN PERIOD

The first recorded event in the geologic history of this region dates back to the Devonian period. At that time the entire area seems to have been submerged beneath the waters of an epicontinental sea, the outlines of which may have been much as indicated on the recently published paleogeographic map of Dr. Bonarelli (1921, plate 7). In the region now occupied by the Sierras de Santa Cruz the calcareous shales and bituminous limestones of the Espejos formation were accumulated in this sea. Farther to the southward the clastic sediments were somewhat coarser and formed the carbonaceous shales and intervening sandy strata of the Los Monos formation. The locality of the Sierra de Mandiyuti seems to have been nearer the shores of this ancient sea than were the areas now occupied by the Sierra de Aguarague; in any event, the equivalent beds in the former place contain a much greater percentage of sand.

The total thickness of these Devonian sediments is not known, but apparently sedimentation was long continued. That epoch seems to have been terminated late in Devonian time by an uplift which changed this portion of the Andean geosyncline to an area of erosion. At the north, between Cochabamba and Santa Cruz, this late Devonian diastrophism crumpled and flexed the newly formed strata into a great series of anticlines and synclines. Toward the south, in the area now occupied by the Front Ranges described herewith, the movement seems to have been a simple uplift.

PERMO-CARBONIFEROUS AND PERMO-TRIASSIC TIME

This region seems not to have again become a site for sedimentation until shortly before the episode of glacial action, which is ordinarily referred to Permo-Carboniferous time. Then the sands, gravel, and muds of the Oquita formation were brought from contiguous highlands and spread broadcast throughout the entire area between Santa Cruz and Embarcacion. In most localities the deposits were probably fluvial, but in places there were shallow lakes or lagoons of considerable extent, and it is possible that for brief intervals parts of the area may have been submerged beneath an epicontinental sea.

With the advance of great ice-sheets over the adjacent land areas, there seems to have been marked augmentation of the loads brought by rivers to this basin. Fluvio-glacial accumulations were piled in great beds until the tremendous thicknesses of the Mandiyuti conglomerate were effected. Glacio-lacustrine beds alternated in some localities with the fluvial deposits; large boulders and occasional masses of till were borne by icebergs to many places remote from the glacier-capped lands.

For some time after the final withdrawal of the Permo-Carboniferous ice this region received deposits of sand and mud, brought by the same streams which had previously been clogged with glacial debris. Great deltas were built near the river mouths, and the finer sediments were spread widely by lake and sea currents. Occasional invasions of marine embayments, apparently from the north, account for the fossil lingulas found in the Machareti beds in the Sierra de Santa Cruz. With apparent abruptness the long episode of clastic sedimentation seems to have given way to widespread seas in which the limestones and cherts of the Vitiacua formation were deposited. This marine condition seems to have been of short duration, however, for it lasted only long enough to permit the accumulation of a comparatively slight thickness of these fossiliferous beds. Its date seems now rather definitely fixed as very late Triassic or early Jurassic.

LATE MESOZOIC TIME

Again the regions of sedimentation were changed to areas of erosion. In some localities there must have been rather definite crustal warping, following the deposition of the Vitiacua limestone and chert, but more commonly the change was effected without notable disturbance. After an interval of unknown duration the accumulation of the Tacuru formation was begun. These beds seem to have been in the main composed of

the sands and muds deposited along the courses of old-age streams or spread widely by currents in shallow lakes or seas. Some appear to have been largely wind-blown sands.

The close of Cretaceous time was probably marked by crustal warping in the region just to the west of that under consideration and by sufficient uplift in the locality of the Front Ranges to terminate sedimentation there.

TERTIARY PERIOD

The greater part of Tertiary time was probably involved in the accumulation of the Tatarenda formation, the result of the many varied agencies responsible for terrestrial sedimentation. In all probability the uppermost of the Tatarenda beds are to be correlated with the strata reported by Berry as carrying marine Pliocene fossils, now at elevations of thirteen and fourteen thousand feet, on the higher slopes of the eastern Andes. In any event, the accumulation of the Tatarenda beds was stopped by pronounced mountain-making movements. These resulted in the breaking and folding of the strata and gave rise to the long, narrow anticlines and tilted fault-blocks of this portion of the Andes. The thrust seems to have come from the west. Its effects were felt farthest toward the east, in the latitude occupied by the Sierra de Charagua. Both to the north and to the south the orogenic movements seem to have been limited to narrower segments of the earth's crust.

QUATERNARY PERIOD

The Pliocene diastrophism started a long interval of erosion which resulted in the formation of a peneplain which may safely be referred to the Pleistocene epoch. This old-age surface beveled the crests of the anticlinal folds and the eastern edges of the tilted fault-blocks. The erosion cycle persisted until only a few low, rounded elevations were left, rising as monadnocks above the lowland plain.

In comparatively recent time, perhaps at the close of the Pleistocene, this old-age surface was uplifted bodily, so that along the front of the Andes its altitude is now 1,500 feet higher than before. The uplift was differential, with greater elevation toward the west than toward the east. Thus the successive remnants of that quondam graded surface are now found at successively higher altitudes when it is traced westward from the front of the Cordillera Oriental toward its center.

The rejuvenated streams quickly lowered their beds in the softer strata, and with the aid of their tributaries etched the landscape into its present form. Thus the topography is that of extreme youth where the resistant Mesozoic and Paleozoic formations are above baselevel, while the soft profiles of the intervening areas have resulted from the swifter progress made possible in the nonresistant Tertiary beds which occupy the intermontane lowland and the Chaco plain.

DECCAN TRAPS AND OTHER PLATEAU BASALTS ¹

BY H. S. WASHINGTON

(Read before the Society December 30, 1921)

CONTENTS

	Page
Introduction.....	765
The Deccan traps.....	766
The Oregonian region.....	775
Thulean basalts.....	780
General discussion.....	780
Iceland.....	781
Faroe Islands.....	785
Other Thulean basalts.....	787
Siberian basalts.....	791
Patagonian basalts.....	793
Algonkian and Palisadan regions.....	795
Conclusions.....	797
Characters of plateau basalts.....	797
Classification of basalts.....	800
Cause of fluidity.....	803

INTRODUCTION

In various parts of the earth and at different geological horizons are large areas covered by very extensive, generally horizontal, series of sheets of basaltic lavas, the series of overlying flows often attaining thicknesses of thousands of meters. In some cases they are accompanied by flows of rhyolite. These basalts have poured out in an evidently very fluid condition, as they occupy preexisting valleys and cover the lower topographic features much like floods of water, the separate flows being very long—many of them measured by miles.

It is generally assumed by volcanologists that these extensive, horizontal, very fluid flows have issued quietly from fissures—an idea first suggested by Sir Archibald Geikie.² Volcanic cones, formed of lavas, ashes, or both, are present in places, but these are inconspicuous, being

¹ Manuscript received by the Secretary of the Society April 28, 1922.

² Geikie: *Nature*, November 4, 1880.

low because of the fluidity of the lavas, and they always form a very minor feature of the complex.

Such lavas are called variously "fissure" or "plateau" flows. The term "plateau" is used here because the word "fissure" connotes the mode of origin, which is still somewhat uncertain. Although "plateau" is commonly connected with some degree of relative elevation above sealevel, yet etymologically it implies only the ideas of flatness and horizontality, which are characteristic of these flows. "Plateau" is used by Geikie, Sollas (Suess), Salisbury, and others in speaking of these lavas.

It is well known that the lavas of these plateau eruptions are mostly basalt, and this petrographical character is the usually accepted explanation of the great extension and horizontality of the sheets, since basalts generally are known to be notably fusible at a lower temperature, and more fluid when fused, than are more silicic lavas. But basalts vary much, both chemically and modally, and many of them are evidently, on extrusion, less fluid than are those of the plateaus. This is especially true of the basalts of many volcanoes of the explosive type, the flows of which do not extend very far and are often found consolidated on steep slopes, as was pointed out nearly one hundred years ago by Lyell.

It is purposed in this paper to take up the question of what character may determine the peculiar fluidity of the plateau basalts as contrasted with the more common ones. Especial attention will be paid to the chemistry of the rocks, inasmuch as this appears to be the controlling factor. It is not intended to enter into geological details or to undertake studies of the areas dealt with. As I have not been able personally to study the flows in the field, and am thus unable to give details as to the relative positions of the various specimens in the series or other such data, my study must be confined to a general one of the chemistry and petrographical characters of the various specimens at my command. The data thus brought together may, it is hoped, serve to supplement the detailed field studies of future geologists in the various regions of plateau basalts.

THE DECCAN TRAPS³

The Deccan traps⁴ were extruded toward the end of the Cretaceous or

³ This is the official designation of the formation adopted by the Geological Survey of India (see Holland, *Mem. Geol. Survey of India*, vol. 43 (1), 1913, p. 40). The name Deccan (from the Sanskrit *dakhshin* = south) denoted originally "that part of the Indian Peninsula which is south of the Vindhyan Range" (Holland). It is now commonly restricted to the central elevated plateau of that region.

⁴ For descriptions see Medlicott, Blanford, and Oldham: *Manual of the Geology of India*, Calcutta, second edition, 1893, pp. 255-284; D. N. Wadia: *Geology of India*, London, 1919, pp. 192-201; F. R. C. Reed: *The Geology of the British Empire*, London, 1921, p. 287. Figure 1 is based on Oldham's map.

possibly in the Lower Eocene. They cover today an area of about 200,000 square miles (that is, about one-seventh of the Indian Peninsula) in central and western India. The main area extends from Cutch and Kathiawar on the northwest to near the southern end of the Bombay Presi-



FIGURE 1.—*Sketch Map of the Distribution of the Deccan Traps*

Showing location of specimens described and analyzed.

- | | | | |
|-----------------|------------------|-----------------|-----------------|
| 1. Panandrao. | 7. Ratnagiri. | 13. Chhindwara. | 19. Jamirapat. |
| 2. Ketool Hill. | 8. Kolhapur. | 14. Amraoti. | 20. Giridih. |
| 3. Kathiawar. | 9. Belgaum. | 15. Mandla. | 21. Rajmahal. |
| 4. Nimach. | 10. Bhopal. | 16. Seoni. | 22. Hyderabad. |
| 5. Nasik. | 11. Hoshangabad. | 17. Balaghat. | 23. Rajamundri. |
| 6. Bombay. | 12. Betul. | 18. Mainpat. | |

dency, along the west coast, and east to Chota Nagpur. There are many small outliers, as in west Sind, and Rajamundri, in Madras, near the east coast; so that, as stated by Wadia, the original extent could not have been less than half a million square miles.

The series of basaltic sheets is not of uniform thickness, reaching a maximum of nearly 10,000 feet along the Bombay coast, being 2,000 to 2,500 feet thick at the southern end, 500 feet at the eastern extremity, and only 100 to 200 feet in the Sind outlier. The average will probably be between 2,000 and 2,500 feet. The average thickness of the individual flows is about 15 feet, with maxima of over 50. Thin layers of ash and some sedimentary deposits are intercalated between many of the flows, especially in the upper part of the series. The flows are shown to have been subaerial. The general horizontality of the sheets is a remarkable feature, and only near Bombay do they dip slightly to the west. Very rarely small flows of rhyolite and trachyte occur with the basalts, as in Gujarat, at the northwest corner. These appear to be due to local differentiation,⁵ but they will not be discussed in this paper because no specimens are at hand for study.

Through the kindness of Drs. L. L. Fermor, Guy C. Pilgrim, and C. S. Fox, the Geological Survey of India have sent me 23 specimens of the Deccan traps, collected in past years from various localities widely scattered over the basaltic area, and I take pleasure in expressing my thanks to the Survey and to these friends for their generosity. Space will not permit detailed descriptions of all the various specimens, so that more or less general descriptions must suffice, leaving the full and detailed treatment to the future work of the Indian petrographers. No detailed petrographic descriptions of the Deccan basalts have been published.

The Deccan basalts are fairly uniform in their megascopic features. The specimens studied by me are all very dark gray or black, many with a slightly brownish tint. They vary in granularity from very dense aphanitic forms, with the semi-resinous luster of tachylitic basalt, through very fine-grained forms (these being the most common), to rather coarse-grained, doleritic forms. They are almost wholly aphyric, the phenocrysts visible megascopically in a few specimens being rare, small, equant crystals of glassy labradorite and a few small and rare olivines in one or two. All my specimens are very compact, but Oldham and Wadia state that vesicular forms are common. The splendid zeolites of these amygdaloidal lavas are well known in collections. Stilbite and apophyllite are common, with less often scolecite, laumontite, and heulandite, all of these being calcic. Glauconite also occurs, as well as much quartz and agate.

Microscopically, these basalts show a rather remarkable uniformity in mode or mineral composition. Plagioclase, chiefly a labradorite of about

⁵ L. L. Fermor: *Rec. Geol. Survey of India*, 1906, p. 34.

the composition Ab_1An_2 , is constant and abundant in all; but neither the highly sodic plagioclases, oligoclase or andesine, nor orthoclase were detected. Augite is also very abundant in the more holocrystalline types, but becomes less so as the glass content increases, and seems to be quite absent in one or two highly glassy specimens. It is gray or, rather more often, slightly brownish, but non-pleochroic. Dr. H. E. Merwin kindly examined the augite of the specimens from Chindwara, Seoni, and Nee-much. He found that the optic axial angle $2V$ is very small, up to about 30 degrees in the plane of symmetry, and obtained the refractive indices $\alpha = 1.700 - 1.710$, and $\gamma = 1.725 - 1.735$. These values correspond to those of an enstatite-augite, and it is of interest to note that Holmes found enstatite-augite to be the common pyroxene in the Arctic basalts, as will be noted later. Labradorite and augite make up about 90 per cent of most of the holocrystalline specimens. Very small amounts of olivine occur in one or two specimens as small, well formed phenocrysts. Irregular grains of magnetite are rather common, and the presence of some leucoxene indicates that this is titaniferous. Very thin plates of ilmenite also occur in a few specimens. Apatite is to be seen here and there, but is not abundant.

The specimens may be referred to four fairly well distinguished textural types, to each of which a few words may be given.

(a) *Coarse, holocrystalline, ophitic*.—Specimens belonging to this type come from Kolhapur* (30/366)⁶ and Nasik,* in the Bombay Presidency; Balaghat (982) and Jamirapat (30/364), in the Central Provinces; and Giridih (3017), in Bengal.

Megascopically, this type is fairly coarse grained and doleritic, black in color, though the specimen from Kolhapur is decidedly brownish. There are no phenocrysts and none of the specimens is vesicular. In thin section they show a typically ophitic texture, the well-twinned labradorite being in sharp tables up to 2 millimeters in length, with anhedral augite intersertal between them. The augite is generally slightly brownish, though the Balaghat specimen contains considerable purplish augite along with some that is colorless; but this specimen appears to be not quite fresh. The augite contains some magnetite grains as inclusions, but no feldspar or glass. The specimen from Nasik is the only one that contains olivine in fairly well formed phenocrystic individuals. Magnetite is rather abundant, generally in irregular grains, but in the Giridih specimen much of it is in thin plates. It is probable that all the magnetite is titaniferous. A few small apatite needles are to be seen, but there

⁶ The numbers in parentheses are those of the India Geological Survey. An asterisk denotes that the specimen has been analyzed.

is no glass, or at least only a minute amount. Analyses of the Kolhapur and the Nasik specimens are given in the accompanying table.

(b) *Coarse, ophitic, subhyaline*.—This type seems to be more common than the preceding and may be divided into two kinds. In the one the glass is very dark, and this is represented by specimens from Amraoti, in Berar (30/356); Mainpat, in Central Provinces (30/365); and Rajamundri,* in Madras (29/321). In the other the glass is yellow, as seen in specimens from Panandrao,* Cutch (3/159), Bhourameta Hill, Chhindwara* (26/172), Padmi,* Mandla (28/557), and Pipardahi* Station, Seoni (28/558), the three last being in the Central Provinces.

Megascopically, this type resembles the holocrystalline one, but the specimens (except Rajamundri) are finer grained and are more generally a slightly greenish black, that from Rajamundri being a decidedly brown black. The specimens with yellow glass appear to be, on the whole, rather finer grained than those with black glass. There is the same glistening of fine feldspar laths as in the preceding type. All the specimens are densely compact except that from Rajamundri, which is rougher and has many minute irregular submiarolitic cavities. Microscopically, this type is much the same as the other, except for the presence of glass. The ophitic texture is identical, as are the labradorite tables and the intersertal augite grains, although the augite of the specimens with yellow glass is decidedly less brown than it is in those with black glass. A little magnetite occurs in this type, but in much less amount than in the holocrystalline one, and in a few cases it is almost entirely lacking. The glass is interstitial between the feldspar and the augites, and its amount is not more than about 10 per cent. The "dark" glass is of a deep brown, which is caused by the presence of abundant "dust" grains. The yellow glass is of a clear, bright, lemon color, and, while most of it is fresh, in some cases it appears to be slightly decomposed, as it shows some aggregate polarization.

(c) *Fine grained, subophitic, holocrystalline*.—The following localities are represented by this type: Ketool Hill, Cutch (3/144); Kathiawar (3/603); Doondea Hill, Hirawari,* Central Provinces (27/165); Belgaum (30/367) and Ratnagiri (30/368), Bombay Presidency; and Hingancy, Hyderabad (29/348).

The basalts of this type are densely aphanitic and compact, without phenocrysts, and of a pure black or slightly brownish or greenish black color. The microscope reveals the same minerals as in the preceding types, but in smaller crystals, the labradorite tables seldom reaching a length of 0.5 millimeter and being generally from 0.1 to 0.3 long. The fabric is somewhat ophitic, but the feldspar tables are more widely scat-

tered and the small augite anhedral are not as strictly intersertal, so that the fabric is more nearly a common basaltic one. The augite grains are pale brown, like that in the coarser types, but of a lighter shade. The specimen from Ketool Hill, Cutch, contains some small subhedral crystals of olivine, and this specimen differs from the others also in that much of the feldspar is in equant, rather than in tabular, crystals. Small grains of magnetite, many of them sharply euhedral, are rather abundant, the specimen from Belgaum showing this mineral (or ilmenite) also in thin tables.

(d) *Fine grained, hyalitic*.—Specimens of this type come from the following localities: Jiran, near Neemuch* (28/556) and Jerkhera, Bhopal (19/238), Central India; Bombay* (1/503); Junapani, His-hangabad (29/567), Central Provinces; and Ramchanderpur, Rajmahal* Hills⁷ (28/704), Bengal.

These specimens are all densely aphanitic and compact, mostly with a dull luster, but that from Bombay shows something of the subresinous luster of tachylyte. They all show a good conchoidal fracture. The color is a deep, pure black, with no tinge of green or brown; no phenocrysts are visible. The texture seen in thin section is a typically basaltic one—very small and sharp, rectangular, relatively thick laths of labradorite and small, equant but rounded grains of slightly brownish augite are irregularly intermingled, with only slight simulation of ophitic fabric and not showing flow texture. Throughout are small, irregular patches of an opaque black substance which the higher powers resolve into a colorless glass densely crowded with black dustlike grains of such small size as to be resolvable with difficulty. In one or two specimens, especially that from the Rajmahal Hills, there are incipient crystallizations of magnetite in lines of minute octahedra branching at right angles. Apart from these and the black grains, which are presumably magnetite, neither magnetite nor ilmenite is present. Olivine seems to be quite absent from these rocks.

Before passing on to the chemical composition of these basalts, a few words may be given to a somewhat striking modal feature. It is clear, from the typically ophitic texture of the more coarsely grained specimens, as well as from the euhedral character of the feldspars and the anhedral forms of the augites in the last type, that the labradorite was the first mineral to crystallize, or at least that it began to crystallize before the augite. This is but another example of a feature that is commonly ob-

⁷ The basalt flows of the Rajmahal Hills belong to the Upper Gondwana and do not properly form part of the Deccan traps. See Wadia: *Geology of India*, 1919, pp. 129, 258; Reed: *The Geology of the British Empire*, 1921, p. 283.

served in basalts. What is of special interest, however, in this connection is the late stage of crystallization of the magnetite and of much of the augite. The rarity of augite and the practical absence of magnetite as inclusions in the feldspars, especially in those of ophitic types, as well as the progressive rarity of well crystallized magnetite with increase in glass content, together with a somewhat less well marked decrease in augite as compared with feldspar as the rock becomes more glassy, point to the conclusion that nearly the whole of the feldspar crystallized first, followed by much of the augite (probably with a period of some simultaneous crystallization), while the magnetite belongs to the latest stage. It would follow that the glass should have a composition corresponding to a mixture of augite and magnetite. That the glass is hydrous is indicated by the uniformly high content in water shown by the analyses, and that the greater portion of this water is original and not brought in by weathering is evident from the very fresh appearance of all the minerals. It would seem to be probable, therefore, that if any differentiation by settling of crystals has taken place in these Deccan flows, we would expect an uppermost layer rich in feldspar, but would not expect a lowermost layer rich in augite or olivine. Only study of the flows in the field can decide whether these expectations are realized or not.

In connection with the late crystallization of augite and magnetite or their replacement by glass, the banded gabbros of Skye at Druim an Eidhne, first described by Geikie and Teall,⁸ are significant and instructive. Here we have a gabbro mass made up of bands, some of highly feldspathic gabbro, others entirely of augite and magnetite, and intermediate bands with less feldspar and hornblende than those of gabbro, but more augite and magnetite, the last frequently inclosing the other minerals. The chemical relations are shown by three analyses, the light gabbro bands having 52.8 per cent of silica, a dark intermediate one 40.2, and an augite-magnetite band 29.5. Here is a striking analogy with what is seen in the Deccan basalts (and also the Oregonian), except that at Skye the plutonic conditions permitted the complete crystallization of the augite-magnetite portion, which solidified as glass in the basalts. One is also reminded of the holocrystalline arapahite (magnetite basalt) of Colorado,⁹ which is composed of 25 per cent of bytownite, 15 of augite, 56 of magnetite, and 4 of apatite. This peculiar magnetite basalt occurs as blocks in a volcanic breccia, and its relations to the ordinary basalts of the region are unknown; but its modal and chemical characters corre-

⁸ Geikie and Teall: *Quart. Jour. Geol. Soc.*, vol. 50, 1894, pp. 643-659. See also Harker: *Rocks of Skye*, pp. 117-121.

⁹ Washington and Larsen: *Jour. Wash. Acad. Sci.*, vol. 3, 1913, p. 449.

spond with what might be expected on the complete crystallization of the vitreous portion of a Deccan or Oregonian basalt.

The crystallization of magnetite in the final stage in much gabbro, norite, and anorthosite (contrary to Rosenbusch's dictum) is discussed recently by Vogt,¹⁰ and he points out that a portion of the magnetite is one of the last minerals to form, even in granitic rocks. The period of crystallization of the magnetite is determined very largely by its percentage amount in the magma; so that if much of it be present, some will crystallize out first, whereas it will be last in rocks poor in magnetite.

So far as I can ascertain from the literature, only four analyses of Deccan traps have been published,¹¹ none of which are satisfactory. I have made 11 analyses of the specimens sent me from the India Survey, endeavoring to obtain a fair idea of the general chemical characters of the whole range of the Deccan traps by analyzing specimens which represented the various textural types and which also represented widely separated portions of the vast area. Many more are doubtless needed to do the region full justice; yet those made will serve to show the general features, especially as there seems to be considerable uniformity among these basalts. The results are presented in Table I.

The most striking feature of this series of analyses is the uniformity in composition of the majority of the basalts, eight of them varying in silica only from 48.6 to 50.1 per cent, while there are three with higher silica, from 53 to 53.46 per cent. The larger group resembles most basalts in all the main features, except that the iron oxides are decidedly high, varying from about 12.6 to 14.5; in the average, 13.1, ferrous oxide dominating greatly over ferric in all. The more silicic group does not show such high iron oxides as is to be expected, but in these also the ferrous oxide is much the higher. Corresponding to this FeO, the amount of MgO is low; so that the augite evidently contains much of the hedenbergite molecule. Potash is notably higher in the more silicic basalts. The CaO is about that which is normal to basalts. Titanium and phosphorus are both in about normal amount, as is manganese, but the absence of chromium is worth noting. Another noteworthy feature of these analyses is the uniformly high water, which applies both to that above and below 110°, although, unexpectedly enough, it is not highest in the more glassy forms. All of the rocks which were analyzed were apparently fresh, so that the presence of water can not be ascribed to weathering.

¹⁰ J. H. L. Vogt: Jour. Geol., vol. 29, 1921, pp. 629, 634.

¹¹ "Bombite" (hyalitic basalt?), Bombay, Dufrenoy, Mineralogie, vol. 4, 1859, p. 289; Traps, Bombay Island, Wynne, Mem. Geol. Survey of India, vol. 5, 1864, p. 196; Basalt, Poonah, Warth, Geol. Mag. (v), vol. 2, 1905, p. 21.

TABLE I
Analyses of Deccan Traps
(The numbers are those of localities on the map)

	8	16	15	12	23	13	5	4	6	21	1	A
SiO ₂	48.62	48.84	49.38	49.83	49.90	49.98	50.12	50.12	52.98	53.45	53.46	50.61
Al ₂ O ₃	14.12	14.37	13.49	11.83	11.98	12.51	12.33	13.52	14.53	15.24	15.50	13.58
Fe ₂ O ₃	2.29	2.63	3.67	3.14	4.55	2.83	4.53	3.99	3.38	1.26	2.81	3.19
FeO	12.40	10.00	8.94	10.92	9.83	11.71	8.04	9.19	10.05	8.20	10.17	9.92
MgO	5.29	5.33	6.48	5.60	5.89	5.42	7.54	5.42	3.66	5.83	3.59	5.46
CaO	9.49	9.82	11.26	9.66	9.80	10.00	9.57	9.97	7.49	9.32	7.61	9.45
Na ₂ O	2.95	2.26	1.68	2.39	2.23	2.65	2.20	2.42	3.43	3.03	3.37	2.60
K ₂ O	0.60	0.52	0.72	0.52	0.47	0.30	0.92	0.56	1.34	1.12	0.84	0.72
H ₂ O+	2.28	2.50	1.42	3.09	0.87	0.95	0.70	1.46	1.88	0.56	1.87	1.70
H ₂ O—	0.63	0.44	0.24	0.35	0.33	0.24	0.81	0.14	0.48	0.47	0.63	0.43
TiO ₂	0.88	2.63	2.16	2.29	3.76	2.27	3.06	2.46	0.62	0.50	0.40	1.91
P ₂ O ₅	0.30	0.36	0.46	0.30	0.21	0.37	0.22	0.29	0.64	0.78	0.31	0.39
Cr ₂ O ₃	none	n. d.	n. d.	n. d.	n. d.	none	n. d.	none	n. d.	n. d.	n. d.	none
MnO	0.21	0.22	0.21	0.21	0.15	0.23	0.14	0.18	0.04	0.13	0.07	0.16
	100.06	99.92	100.11	100.13	99.97	99.55*	100.18	99.84†	100.12	99.89	100.63	100.12
Sp. gr.	3.050	2.927	2.926	3.006	2.986	2.975	2.954	2.903	2.831	2.886	2.855	2.916
	22.8°	22°	22°	22°	22.8°	22.8°	23°	23°	22.8°	22.8°	22°	
8. (30/366). Station bungalow, Kolhapur State. III.5.3(4). (4)5.												
16. (28/558). Pipardahi station, Seoni, Central Provinces. III."5.4. (4)5.												
15. (28/557). Padmi, Mandla, Central Provinces. III."5.4.4.												
12. (27/165). Doondea Hill, Hiraswari, Central Provinces. III."5.3(4). (4)5.												
23. (29/321). Katem quarries, Rajamundri, Madras. III."4."4. (4)5.												
13. (26/172). Bhourameta Hill, Chindwara, Central Provinces. III."5. (3)4.5.												
5. (16/757). Igatpuri, Nasik, Bombay Presidency. III."4.5. (3)4.4.												
4. (28/556). Jiran, near Nimach, Central India. III."5."4.4(5).												
6. (1/503). Between Race Hill and Scoree, Island of Bombay. (II)III."5.3.4.												
21. (28/704). Ramchanderpur, Rajmahal Hills, Bengal. (II)III."5.3".4.												
1. (3/159). Panand Rao, Cutch. II(III)."5.3".4(5).												
A. Average of 11 analyses. III."5.3(4).4".												

* Includes ZrO₂, none; SO₃, 0.09; BaO, none; SrO, none.

† Includes ZrO₂, none; SO₃, 0.09; BaO, 0.03.

It seems scarcely necessary to give the norms of all the analyses; so that those of only four, the two extremes of the less silicic types and two of the more silicic, are given in Table II, with the norm of the average composition.

TABLE II

Norms of Deccan Traps

	1	2	3	4	5
Quartz		5.46	2.40	4.38	4.14
Orthoclase	3.34	5.56	6.67	7.78	4.45
Albite	25.15	18.34	25.68	28.82	22.01
Anorthite	23.35	21.13	24.46	20.29	23.07
Diopside	18.40	19.55	13.98	10.74	17.41
Hypersthene	13.68	15.53	21.16	18.58	17.78
Olivine	7.49	.....	.....	.....	.....
Magnetite	3.25	6.50	1.86	4.87	4.64
Ilmenite	1.67	5.93	0.91	1.22	3.65
Apatite	0.67	0.67	1.68	1.51	1.01

1. Kolhapur. III.5.3(4).(4)5.
2. Nasik. III.(4)5.(3)4.4.
3. Rajmahal Hills. (II)III.5.3".4.
4. Bombay. (II)III."5.3.4.
5. Average of 11. III."5.3(4).4".

These norms show some rather interesting features. That of the Kolhapur basalt (number 1) is the only one in which quartz does not occur and in which olivine is a femic constituent. A notable amount of quartz occurs in the norm of even the olivine-bearing Nasik basalt (number 2). The amounts of albite and anorthite are about equal to each other in all the norms, this being well seen in the average, the albite increasing in the more silicic rocks, as does the orthoclase. The molecules of diopside and hypersthene are also in general present in about equal amount, as the average norm shows, but that of diopside is somewhat in excess in the less silicic group, and that of hypersthene in the more silicic. The very considerable amount of normative hypersthene is in harmony with the observation that the pyroxene is an enstatite-augite, as determined by Merwin.

THE OREGONIAN REGION

In the extreme northwestern corner of the United States—in southern Idaho, northern Oregon, and southern Washington—there is an extensive area covered by thick horizontal flows of basalt. These are commonly known as the Columbia River and Snake River basalts, from the valleys which they chiefly occupy. The term "Oregonian" is applied here to this

region because the name "Oregon" was originally given, so far back as 1778, to the river now called the Columbia, and was afterward applied, somewhat vaguely, to the country drained by this river. The name was preserved for many years in that of the old Oregon Trail.¹²

The basaltic flows which occupy the two river valleys and the surrounding country belong obviously to one comagmatic region, and may therefore be discussed together. Parts of the region have been described more or less by many writers, of whom only a few may be cited here.¹³ The region as a whole, however, has never been adequately treated and a monographic description of the whole region is much to be desired. Nearly all those who describe these flows remark on their similarity to the Deccan traps.

The area covered at present by the Oregonian basalts is at least 200,000 or 250,000 square miles, approximately that of the Deccan traps¹⁴. The maximum thickness of the series of flows is about 4,000 feet, and Campbell calculates the total volume as 24,000 cubic miles, assuming an average thickness of only 500 feet. The number and thickness of the separate flows differ at different localities, and the average thickness appears not to have been estimated. The basalts were considered by Geikie to have issued from fissures, and Russell, Campbell, and practically all others concur in this view. Some low, broad cones, made up of ash or flows or both, occur throughout the area, especially on the Snake River plateau, but they are inconspicuous and constitute a minor feature. Some ash beds and layers of soil are intercalated between the beds in places, and volcanic bombs are fairly common. Pre-Tertiary rhyolites occur with the basalts, but the relation between these rhyolites and the basalts is not clear, and no analyses of these rhyolites seem to have been published. The great extension and substantial horizontality of the Oregonian basalts and the striking way in which, water-like, they flowed over and submerged the preexisting topographic features, indicating a high degree of fluidity, are the chief physical characters of the region, in which it is at one with that of the Deccan.

The age of the earlier of the Oregonian flows is assigned to the Eocene, and the flows seem to have reached their maximum in the Miocene; but Russell thinks that flows "occurred probably within recent historical times and are, perhaps, not over 100 to 150 years old." The flows of the

¹² Cf. F. W. Hodge: *Handbook of American Indians*. Bureau American Ethnology, Bull. 30, vol. ii, 1912, p. 146; J. S. Diller: *U. S. Geol. Survey, Bull.* 614, 1915, p. 28.

¹³ I. C. Russell: *Volcanoes of North America*. New York, 1897, pp. 250-257; Russell: *U. S. Geol. Survey, Bull.* 199, 1902; G. O. Smith: *U. S. Geol. Survey, Folio* 106, 1904; M. R. Campbell et al.: *U. S. Geol. Survey, Bull.* 611, 1915, pp. 165-168.

¹⁴ A sketch map is given by Campbell, *op. cit.*, sheet 23.

Columbia River valley are much more recent than those of the Snake River in Idaho.

I have studied but few specimens of the Oregonian basalts—fewer, indeed, than of the Deccan traps. I am indebted to Dr. A. C. Spencer and Prof. R. W. Chaney for some specimens, and to the United States National Museum for others. This paucity of material is to be regretted, as there seems to be more variety among these basalts than in those of India. It is hoped, however, to make a more complete study of them, supplemented by study of the accompanying rhyolites, at another time.

Megascopically, the Oregonian basalts vary in texture from rather coarse-grained, doleritic forms to dense aphanitic ones, phenocrysts (of labradorite) being rather rare. The color of the coarser forms is a blackish brown, while that of those which are fine grained is a dark gray to black.

Brief descriptions of the specimens analyzed will suffice to indicate the microscopic characters. The Dalles (Oregon) basalt is the most coarse grained and in thin section is seen to be typically ophitic, with numerous tables of labradorite and interstitial slightly brownish augite present in about equal amounts. There is considerable magnetite, part of it in thin plates, which penetrates both the feldspar tables and the augite grains. Well formed small octahedra of magnetite also occur. There is a little residual glass, which was apparently originally colorless, but is now a pale bluish green, through chloritic decomposition. The Idaho Falls specimen is similar, but is not quite so coarse grained and is less typically ophitic. This contains relatively much more feldspar and less (colorless) augite than the Dalles rock, and magnetite is practically absent. On the other hand, there is much more glass, which appears to be black under low powers, but which a high power shows is so crowded with excessively minute "dust" grains as to appear almost opaque. A specimen from Shoshone Falls (Idaho), collected by Spencer, is megascopically very fine grained and dark gray; it shows in thin section a typically basaltic texture, with marked flow fabric. Small, short tables of labradorite are intermingled with anhedral grains of almost colorless augite, the two minerals in about equal amount, and with rather numerous, fair-sized, anhedral grains of magnetite. Each of the three minerals incloses and forms inclusions in the other, and the crystallization of all three must have been in great part contemporaneous, although crystallization began apparently with the feldspar. The Shoshone Falls specimen is holocrystalline. None of the basalts which I analyzed contains olivine.

The Teanaway basalt, described by Smith, seems to be much like the Dalles and Idaho Falls specimens, while that of Yakima, although similar

in general, contains small and variable amounts of olivine. This is the more noteworthy in view of its silica content being the highest of those in the table of analyses.

The chemical characters of the Oregonian basalts are shown by the analyses in Table III. From these it will be seen that there is much more variation among them than was noted in those of the Deccan and no apparent division into two groups. Silica, for instance, varies from 45.16 to 54.50 per cent, but there is less variation among the other constituents. In this region we find, as we did in India, that the most characteristic feature is the very high percentage of iron oxides (except in number 6), with ferrous oxide predominating strongly over ferric in all of them. Some of the ferrous oxide percentages, indeed, are exceptionally high for basalts. Magnesia is low in general, the augite being evidently strongly hedenbergitic, as in the Deccan, while lime is in about the usual amounts. Although soda dominates over potash, there is more of the latter in the Oregonian basalts than in the Indian, and this may possibly be connected with the occurrence of rhyolites. Titanium, phosphorus, and manganese are all decidedly high, except again in the Yakima basalt, which does not seem to be representative of the region, as has been thought. An incomplete analysis by Merrill of the basalt of Walla Walla, Washington, shows the same general features as those more completely analyzed.¹⁵ These general characters are well shown in the average (number 7), which it is instructive to compare with that of the Deccan traps.

¹⁵ W. Lindgren: U. S. Geological Survey, Prof. Paper 27, 1904, p. 75. The analysis is as follows: SiO_2 , 47.35; $\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$, 34.38; FeO , n. d.; MgO , 4.43; CaO , 8.27; Na_2O , 2.55; K_2O , 1.33; H_2O , 0.95; Sum, 99.26.

TABLE III
Analyses of Oregonian Basalts

	1	2	3	4	5	6	7
SiO ₂	45.16	46.67	49.08	51.14	53.35	54.50	49.98
Al ₂ O ₃	13.51	13.96	13.71	13.95	12.90	14.43	13.74
Fe ₂ O ₃	4.36	1.66	1.25	2.15	2.64	2.17	2.37
FeO	11.05	12.48	13.02	12.97	11.28	8.80	11.60
MgO	7.55	7.09	4.58	2.21	2.68	4.24	4.73
CaO	9.71	9.55	8.44	6.56	6.96	8.01	8.21
Na ₂ O	2.38	2.48	3.17	3.59	2.83	3.05	2.92
K ₂ O	0.58	0.84	1.31	2.33	1.40	1.29	1.29
H ₂ O+	0.89	0.82	0.90	0.22	1.76	1.09	0.95
H ₂ O—	0.04	0.08	0.20	0.12	0.91	0.29	0.27
TiO ₂	3.88	3.22	3.56	2.41	2.44	1.69	2.87
P ₂ O ₅	0.87	0.82	0.73	1.59	0.45	0.21	0.78
Cr ₂ O ₃	none	n. d.	n. d.	none	none	n. d.	none
MnO	0.19	0.18	0.25	0.44	0.25	0.10	0.24
	100.07	99.85	100.20	100.30*	100.07†	100.13‡	99.95

1. Shoshone Falls, Snake River, Idaho; Washington, analyst.
2. Idaho Falls, Snake River, Idaho; Washington, analyst.
3. The Dalles, Columbia River, Oregon; Washington, analyst.
4. Cinder Buttes, Snake River, Idaho; Hillebrand, analyst. I. C. Russell, United States Geological Survey Bulletin 199, 1902, page 87.
5. Teanaway River, Kittitas County, Washington; Hillebrand, analyst. G. O. Smith, United States Geological Survey Folio 106, 1904, page 6.
6. Yakima basalt, Clalum Ridge, Washington; Steiger, analyst. G. O. Smith, United States Geological Survey Folio 106, 1904, page 8.
7. Average of the six analyses above.

The norms of the Oregonian basalts are shown in Table IV, those of all of them being given, as there is so much variety among them.

TABLE IV
Norms of Oregonian Basalts

	1	2	3	4	5	6	7
Q .....	.....	.....	.....	1.56	10.32	7.08	2.16
Or	1.67	5.00	7.78	13.34	8.34	7.78	7.78
Ab	20.44	20.96	26.72	30.39	23.58	25.68	24.63
An	24.74	24.46	19.18	15.29	18.35	21.68	20.57
Di	14.87	14.44	15.13	5.98	11.33	14.29	12.03
Hy	15.47	14.26	16.57	21.43	15.46	15.12	20.72
Ol	6.01	9.31	3.16	.....	.....	.....	.....
Mt	6.26	2.32	1.86	3.02	3.71	3.25	3.48
Il	7.45	6.08	6.84	4.56	4.71	3.19	5.47
Ap	2.02	2.02	2.31	3.70	1.01	0.34	2.02

* Includes ZrO₂, 0.12; F, 0.10; FeS₂, 0.15; NiO, trace; BaO, 0.25; SrO, trace.

† Includes FeS₂, 0.13; V₂O₃, 0.04; NiO, trace; BaO, 0.05; SrO, trace.

‡ Includes SO₃, 0.11; NiO, none; BaO, 0.06; SrO, 0.09.

On the one hand, these norms show, as do the analyses, the greater variation among the Oregonian as compared with the Deccan basalts. Nearly half of them contain olivine and no quartz, and the quartz content of the Teanaway and Yakima basalts is higher than in any of the Indian ones. On the other hand, we see here much the same general characteristic features as we did in the previous series. There is the same general equality in the amounts of albite and anorthite, with albite relatively higher in the more silicic rocks, as is also orthoclase. Diopside and hypersthene are again approximately equal, but here there is not the general increase in hypersthene as compared with diopside that was noted before. The augite here also is evidently an enstatite-augite.

THULEAN BASALTS

GENERAL DISCUSSION

We now take up for consideration a third great area of plateau basalts, which were poured out (for the most part probably during the Eocene) over the large landmass that once occupied much of the present north Atlantic and of which only a few small and disconnected fragments survive.¹⁶

Fragments of this extensive basaltic area are found in northern Ireland, western Scotland, east Greenland (and possibly in west Greenland), and the islands of the Hebrides, Shetlands, Orkneys, Faroes, Iceland, Jan Mayen, Spitzbergen, and Franz Josef Land. The essential similarity and presumably common origin and relationship of these basalt flows have been generally recognized by those who have written on the region. I have been able to study specimens from only Iceland and the Faroe Islands, but the basalts of other parts will be described briefly, so as to give a general idea of the whole region.

The name "Brito-Arctic" has been applied to this region by British petrologists, but this appellation is open to the objection that only small parts of Great Britain and of the Arctic are included in it. The name "Thulean," proposed here for this region of plateau basalts, is derived from the name *Thule*, given by Pytheas toward the end of the fourth century B. C. to a somewhat vague and as yet undefined and not wholly identified island or region lying to the north of the British Islands. It seems advisable thus to distinguish the basaltic plateau from the De-

¹⁶ The literature on this region and its rocks is so abundant and varied that only a few references, of a more general character, need be cited. Geikie: *Ancient volcanoes of Great Britain*, vol. ii, 1897, pp. 181-297; *Textbook of Geology*, vol. i, p. 345; vol. ii, 1903, p. 1252; Harker: *Natural history of igneous rocks*, 1909, pp. 19 and 99; Suess: *The face of the earth* (English translation), vol. iv, 1909, pp. 258-267; Holmes and Harwood: *Min. Mag.*, vol. 18, 1918, p. 180.

vonian continent of *Eria*, of whose area the Thulean region forms but a part, distinguished especially by its basaltic flows.

The general origin, character, extent, and structure of the Thulean region are well and concisely described by Harker,¹⁷ whom we may quote here:

"These events characterized by a regional extension may be summarized as, first, the outpouring of enormous quantities of lava; second, the intrusion of innumerable sills; and, third, the injection of a great system of dikes. The lavas, which can be assigned to an Eocene age, did not emanate from great central volcanoes, but, as Sir Archibald Geikie has shown, welled up through innumerable fissures. The individual flows were not large, but collectively they covered a very extensive region. Indeed, for any evidence to the contrary, a continuous lava field may have stretched from Antrim to beyond Franz Josef Land, a distance of 2,000 miles. . . . Petrographically, these extrusions and intrusions are characterized by an overwhelming preponderance of basic types, with an alkaline tendency which is sometimes rather latent than expressed, but sometimes strongly marked."

ICELAND¹⁸

Although basalts make up by far the greater proportion of the lavas of Iceland, they have been less studied petrographically than the much less abundant rhyolites and toscanites. The Iceland basalts are somewhat indefinitely referred by the authors cited above to three general periods of eruption: the Tertiary plateau basalts, which attain a total thickness of over 3,000 meters, according to Geikie and Hawkes; later pre-Glacial, Glacial, and post-Glacial flows; and the modern basaltic eruptions. While the first seem to have been predominately, if not exclusively, fissure eruptions, like those of the Deccan and Oregon regions, the flows of the second and third periods were frequently accompanied by the formation of low "shield" volcanoes, composed mostly of lava with very little ash, and which are compared by Reck with Kilauea and other Hawaiian volcanoes. None of the basaltic volcanoes of Iceland, even the most recent, appear to be truly strato-volcanoes of the Vesuvius or Etna type, although some minor explosion craters, hornitos, and other such minor phenomena are to be found.

The Icelandic basalts of all three periods show both porphyritic and non-porphyritic habits, and in both of these there are represented olivine-

¹⁷ A. Harker: Some aspects of igneous action in Britain. *Quart. Jour. Geol. Soc.*, vol. 73, 1918, pp. xci-xciii.

¹⁸ For some descriptions of the basalts and basaltic volcanoes of Iceland, see A. Geikie: *Ancient volcanoes of Great Britain*, vol. 2, chapter xl, 1897; Thoroddsen: *Island. Peterm. Mitth.*, Erg. Heft no. 152, 1905; H. Reck: *Isländische Masseneruptionen*, *Geol. Pal. Abh. von Koken*, vol. 9, Heft 2, 1910; L. Hawkes: *Geol. Mag.*, 1916, p. 385; A. Holmes: *Min. Mag.*, vol. 18, 1918, p. 190.

free and olivine-bearing modes, although the former seem to be much the more common. Through the kindness of Dr. Fred E. Wright, who visited Iceland in 1909, I was able to study several specimens collected by him. Three of these were analyzed. Of the two older basalts, one is from Allamannagja, near Thingvellir, and is probably post-Glacial, while the other, from Reykjavik, is pre-Glacial; a third is from a modern flow of Hecla. The first two are medium gray, rather rough basalts, with many small (not over 1 millimeter) phenocrysts of feldspar; the Hecla specimen is a gray-black, densely aphanitic and without phenocrysts. One of Holmes' (analyzed) specimens, from Grunda Fjord, in the southwest peninsula, of Quaternary age, shows small phenocrysts of olivine, but none of feldspar; another, from Holmatindur, on the Eski-fjord (east Iceland), would seem to represent the Tertiary plateau flows, and is a dense, quite aphyric basalt of a dark gray color.

In thin section my three specimens are much alike. They are composed almost wholly of thin tables of rather calcic labradorite and subophitic anhedra or ophitic patches of an almost colorless or slightly greenish brown augite, which Holmes determined to be enstatite-augite. There are rare and small crystals of olivine and apatite, but neither magnetite nor ilmenite is visible in my sections. All of them carry considerable colorless, very dusty glass, the Hecla specimen in most abundance. The specimens analyzed by Harwood for Holmes are much the same, except that they contain a few olivine phenocrysts and considerable ilmenite, but either little or no glass. We see, therefore, the same relation between "ores" and glass that was observed in the basalts of the Deccan and Oregon regions. The Eski-fjord basalt of Holmes contains about 1 per cent of calcite, which he regards as primary.

In Table V are given the analyses of my three specimens, with others of Icelandic basalts.

TABLE V

Analyses of Iceland Basalts

	1	2	3	4	5	6	7	8
SiO ₂	48.79	47.27	48.06	47.67	53.39	49.67	46.97	49.04
Al ₂ O ₃	11.96	14.44	12.14	15.81	13.37	13.57	13.87	13.54
Fe ₂ O ₃	2.51	0.97	4.89	1.70	2.07	7.79	8.27	2.43
FeO	12.10	10.15	9.04	10.41	10.62	7.21	5.76	10.46
MgO	5.60	10.30	9.80	8.08	3.30	5.53	4.76	7.42
CaO	10.15	11.73	12.23	12.23	6.90	12.37	14.46	10.55
Na ₂ O	2.40	1.86	2.07	1.98	3.84	1.57	1.75	2.43
K ₂ O	0.70	0.18	0.31	0.27	1.19	1.20	0.45	0.53
H ₂ O+	0.40	0.33	0.10	0.21	1.37	0.15	n. d.	0.48
H ₂ O—	0.65	0.09	0.04	0.10	0.08	....	n. d.	0.19
CO ₂	0.41	none	none	none	none	n. d.	n. d.	none
TiO ₂	4.17	2.36	1.55	2.17	2.28	1.50	1.99	2.51
P ₂ O ₅	0.37	0.12	0.07	0.10	1.24	n. d.	n. d.	0.38
S	0.06	none	0.01	n. d.	n. d.	n. d.	n. d.	....
Cr ₂ O ₃	trace	0.04	none	n. d.	n. d.	n. d.	n. d.	....
V ₂ O ₅	0.11	0.07	n. d.	n. d.	n. d.	n. d.	n. d.	....
MnO	0.21	0.19	0.17	0.16	0.20	n. d.	1.20	0.20
	100.59*	100.12†	100.48‡	100.89	99.85	100.56	99.48	100.26

1. Basalt (Tertiary). Holmatindur, Eski-fjord; Harwood, analyst. Holmes, Mineralogical Magazine, volume 18, 1918, page 193.
2. Olivine basalt (Quaternary). Grunda-fjord; Harwood, analyst. Holmes, Mineralogical Magazine, volume 18, 1918, page 196.
3. Basalt (pre-Glacial). Reykjavik; Washington, analyst.
4. Basalt (post-Glacial). Allamannagja, near Thingvellir; Washington, analyst.
5. Basalt (Recent). Near Naefurholt, Mount Hecla; Washington, analyst.
6. Basalt (Recent). Hecla. Rosenbusch, Elem. Gest., 1910, page 399.
7. Basalt (Recent?). Randholar Volcano; Hauser, analyst. Komorowicz, Vulk. Stud. Ins. Atlant., 1912, page 25.
8. Basalt. Iceland. Mean of numbers 1, 2, 3, 4, and 5.

With the exception of Wright's specimen of the Hecla basalt, which is notably higher in silica, alkalies, and phosphorus, but lower in magnesia and lime, these basalts much resemble each other. There are a few points of difference, such as the different iron oxides of number 3 and the lower magnesia of number 1, but the first four are alike in showing rather high iron oxides, with ferrous oxide preponderant over ferric—strikingly so except in number 3. The other characters call for no special comment here, being much like those of the basalts previously studied.

* Includes Cl, trace; NiO, trace; BaO, trace; SrO, none.

† Includes Cl, 0.01; NiO, 0.01; BaO, none; SrO, none.

‡ Includes ZrO₂, none; BaO, none.

Attention should, however, be called to the figures for chromium, and especially vanadium, shown in Harwood's complete and excellent analyses. In this they resemble the Faroe basalt analyzed by him and, as we shall see, many other basalts of this region. Hauser's analysis (number 7) is so unsatisfactory as not to merit discussion, except to point out that in its general features it much resembles the first five.

The norms of these basalts (except number 6) are given in Table VI.

TABLE VI
Norms of Iceland Basalts

	1	2	3	4	5	A
Quartz	3.60	.....	.....	.....	5.88	.....
Orthoclase	3.89	1.11	1.67	1.67	7.23	3.34
Albite	20.44	15.72	17.82	16.77	32.49	20.96
Anorthite	20.02	30.30	22.80	33.36	15.57	24.19
Diopside	20.66	21.88	30.34	21.58	9.34	20.93
Hypersthene	17.38	10.83	10.87	10.89	17.66	18.92
Olivine .....	.....	13.50	6.48	9.20	.....	2.11
Magnetite	3.71	1.39	7.19	2.55	3.02	3.48
Ilmenite	7.90	4.56	2.89	4.26	4.41	4.71
Apatite	1.01	0.34	.....	0.34	2.69	1.01

1. Holmatindur. III."5.3(4).4(5).
2. Grunda-fjord. III.5.4."5.
3. Reykjavik. III".5."4."5.
4. Allamannagja. III.5.4."5.
5. Hecla. (II)III.(4)5."3.4.
- A. Average. III.5."4.4(5).

These norms show much the same features that we have observed before. Several of the basalts show excess silica, while others show considerable olivine, but none contain the nephelite molecule. It is noteworthy that only the earliest and the latest basalts are quaric, and it is to be seen that the normative feldspar of these two contains a much greater proportion of albite to anorthite than do the others. In Wright's Hecla specimen the feldspar is about Ab_4An_3 , in those from Holmatindur, Reykjavik, and in the average it is about Ab_1An_2 , while in the Grunda-fjord and Allamannagja rocks it is about Ab_1An_4 . It is also noteworthy that in most of these norms the amounts of diopside and of hypersthene or of hypersthene and olivine are approximately equal, as is evident from the norm of the average rock; but at Reykjavik the amount of diopside is about double that of the non-calcic femic silicates, while the reverse is true of the Hecla specimen. The general relations of these femic molecules are corroborative of Holmes' determination of the pyroxene as an

enstatite-augite. The amounts of magnetite and ilmenite are decidedly high in all the rocks.

The relations of these basalts to the rhyolitic or toscanitic lavas are little known and can not be discussed here. These more silicic rocks would seem to have been erupted, contemporaneously with basaltic flows, from Tertiary times down almost to the present. With one or two exceptions, the analyses that we have of them, such as those of Bäckström,¹⁹ are not very satisfactory, but, so far as they go, they indicate a very considerable degree of variation, silica ranging from 79 to 63 per cent and the alkalis varying very much in their mutual relations.

FAROE ISLANDS²⁰

These islands are made up very largely of numerous almost horizontal sheets of basalt, which dip slightly through subsidence and which average about 50 feet in thickness. They are accompanied by sills, dikes, and necks. The petrography of these lavas has been little studied, an early paper by Osann²¹ and a recent one by Holmes²² giving almost all the information concerning this that we have.

It would appear that there are two main types of Faroe basalt: one porphyritic, with phenocrysts of labradorite, and the other dense and aphyric. Holmes describes and gives figures of both types, and there would appear to be little difference between them, except for the feldspar phenocrysts. The only specimen examined by me was collected near the harbor of Thorshavn, on the Island of Stromoe, by Dr. Wright, who very kindly turned it over to me for study. It is a slightly vesicular basalt, showing rather numerous thick, tabular phenocrysts of labradorite, up to about 1 centimeter long, in a densely aphanitic, dark gray groundmass.

In thin section the Thorshavn specimen shows a porphyritic subophitic texture. The labradorite phenocrysts are rather euhedral, un-twinned for the most part, and without zonal structure. There are no phenocrysts of either pyroxene or olivine. The groundmass is made up in great part of small tables of labradorite, which are multiply twinned and with extinction angles that indicate a composition not quite as calcic as Ab_1An_2 . Between these, in less amount, are small anhedral grains, rather than true ophitic areas, of a colorless augite, with very few and small grains of olivine, very rare grains of ore, and some small prisms of apatite. There is considerable interstitial, somewhat cloudy, glass, but

¹⁹ H. Bäckström: *Geol. For. Forh.*, vol. 13, 1891, p. 668.

²⁰ For the geology of the Faroes, see A. Geikie: *Ancient Volcanoes of Great Britain*, vol. ii, pp. 191, 192, 256, 322; and Cornu and Gorgey: *Neues Jahrb., Centralbl.*, 1908, pp. 675-684 (map).

²¹ A. Osann: *Neues Jahrb.*, 1884, vol. i, p. 45.

²² A. Holmes: *Geol. Mag.*, 1918, vol. —, p. 199.

the rock appears to be very fresh. No nephelite could be detected. The section of the specimen examined by me differs from one from Thorshavn described and figured by Holmes, in that the latter shows much more ilmenite-magnetite and seems to be free from glass. According to Holmes, the aphyric specimen from Waags-fjord is much like the other, except that microphenocrysts of labradorite replace the megaphenocrysts of the Thorshavn rock, and augite ("enstatite-augite") is somewhat more abundant. Crystals of "ilmenite" are very abundant, and this mineral seems to have been among the last to crystallize out.

An analysis by me of the porphyritic Thorshavn basalt and one by Harwood of the aphyric Waags-fjord rock are given in Table VII, with the average of the two. The two analyses are much alike as regards many of the constituents, but the porphyritic lava is lower in silica, ferrous oxide, and titanium, but higher in alumina and soda. The differences correspond with its porphyritic and more feldspathic character and the less calcic composition of the plagioclase.

TABLE VII
Analyses of Faroe Basalts

	1	2	3
SiO ₂	47.58	49.70	48.64
Al ₂ O ₃	17.12	10.98	14.05
Fe ₂ O ₃	3.03	3.02	3.03
FeO	8.73	11.19	9.96
MgO	5.18	5.34	5.26
CaO	10.12	9.71	9.92
Na ₂ O	3.89	2.22	3.06
K ₂ O	0.86	0.63	0.75
H ₂ O+	0.13	0.96	0.55
H ₂ O—	0.06	0.92	0.49
TiO ₂	2.72	4.83	3.78
P ₂ O ₅	0.41	0.33	0.38
Cl	n. d.	0.02	....
S	n. d.	0.05	....
V ₂ O ₃	n. d.	0.03	....
MnO	0.14	0.22	0.18
	99.97	100.18*	100.05

1. Basalt, porphyritic. Thorshavn, Stromoe; Washington, analyst.
2. Basalt, aphyric. Waags-fjord, Suderoe; Harwood, analyst. Holmes, Geological Magazine, 1918, page 201.
3. Basalt, Faroe Islands. Average of above.

* Includes Cr₂O₃, trace; NiO, none; BaO, 0.01; SrO, none.

The norms of these analyses are given in the Table VIII below. They are alike in that albite and anorthite are present in almost equal amounts in either, although the porphyritic lava shows much more of both than does the other. They differ notably, however, in that the Thorshavn basalt shows no normative quartz, but, on the contrary, a little nephelite and some olivine, while that of Waags-fjord is decidedly quaric, having nearly 8 per cent of excess silica, and hypersthene instead of olivine. These differences are expressed in the symbols given. Inasmuch as no trace of nephelite is visible in the sections of the Thorshavn rock, it may be supposed that the normative nephelite is represented modally by the carnegieite molecule in the abundant feldspar, and it would be of interest to separate and analyze the feldspar phenocrysts were sufficient material available.

TABLE VIII
Norms of Faroe Basalts

	1	2	3
Quartz		7.98	0.60
Orthoclase	5.00	3.89	4.45
Albite	27.77	18.34	25.15
Anorthite	26.69	18.35	22.52
Nephelite	2.84	.....	.....
Diopside	16.81	22.07	19.34
Hypersthene		13.14	14.54
Olivine	10.02	.....	.....
Magnetite	4.41	4.41	4.41
Ilmenite	5.17	9.12	7.30
Apatite	1.01	1.01	1.01

1. Thorshavn, Stromoe. (II) III.5.3.4(5).
2. Waags-fjord, Suderoe. III.4".3(4).4".
3. Average, Faroe Islands. III.5.3".4".

OTHER THULEAN BASALTS

Since I have been unable personally to study any Thulean basalts other than those of Iceland and the Faroes, a few words must suffice for the others, so that we may obtain a conspectus of the region. The more important references are given in each case.

The plateau basalts of western Scotland, northern Ireland, the Hebrides, and Orkneys have been quite fully described in numerous papers by Geikie, Judd, Teall, Harker, Peach and Horne, Flett, and many other British petrographers.²³ We may take the flows of Skye, well described

²³ See, for instance, Geikie: *Ancient volcanoes of Great Britain*, vol. ii, 1897; Harker: *Tertiary igneous rocks of Skye*, 1904; Flett: *Trans. Roy. Soc. Edinburgh*, vol. 39, 1900.

by Harker, as typical of those of the subregion. The Skye flows were subaerial and issued from fissures. They are of enormous volume in the aggregate, the total thickness of the series of flows (and sills) being over 2,000 feet, the individual flows being from 20 to 50 feet thick. They "show on the whole a remarkable uniformity of general character," two textural types being present, one porphyritic, with labradorite phenocrysts, and the other densely aphyric. The micro-texture is usually ophitic, and they are composed, as are the other plateau basalts, of labradorite and augite, with minor amounts of magnetite and apatite. Glass seems to be comparatively rare. Exceptionally, olivine is present, rarely as phenocrysts, and a few show phenocrysts of augite. The general chemical characters are shown by the average given in Table IX, from analyses given by Harker. The basalts appear to be, in general, not quite fresh, which would explain the somewhat low silica and relatively high ferric oxide. Harker (page 249) notes that Pollard determined quite notable amounts of chromium and vanadium in a number of them, which is in accord with the observations of Harwood and Holmes elsewhere.

In *Greenland* there are two now distinct, but probably formerly connected, areas of plateau basalts. The one is on the west coast and includes the basalts of Disco²⁴ and Hare²⁵ Islands. These form thick and fairly extensive, horizontal flows, of ophitic texture and generally aphyric. They have the usual composition of the plateau basalts, except that the Disco basalts contain variable amounts of metallic iron, while the Hare Island rocks seem to be free from this, but contain more or less olivine as phenocrysts. An average of analyses of these West Greenland basalts is given in Table IX. Little is known of the basalts of the two great basaltic areas along the east coast of Greenland, but they would seem to be much like the other Thulean basalts.²⁶ There is only one analysis of them, but as the rock is not fresh, the analysis is not reproduced here.

Of the rocks of *Jan Mayen* there is very scanty information. They are predominantly basalts, but an ægirite trachyte occurs, and the descriptions of Scharizer²⁷ and Holmes²⁸ indicate that the rocks have decidedly alkalic affinities. The basalts described do not greatly resemble the usual Thulean or other plateau basalts, as the texture is not notably ophitic, the plagioclase contains much more of the albite molecule, nephelite is present in some, and olivine seems to be common. The specimen analyzed by Harwood contained about 5 per cent of calcite, which Holmes regards as primary.

²⁴ T. Nicolau: Meddel. Groenl., vol. 24, 1901, p. 215.

²⁵ Holmes and Harwood: Min. Mag., vol. 18, 1918, p. 182.

²⁶ Holmes and Harwood: Op. cit., p. 189.

²⁷ R. Scharizer: Jahrb. geol. Reichsanst. Wien, vol. 34, 1884, p. 707.

²⁸ Holmes and Harwood: Min. Mag., vol. 18, 1918, p. 202.

The rocks of the *Spitzbergen* group (including King Charles Land) are fairly well known and we have several analyses of them.²⁹ The lavas are mostly basalts, but some "trachydolerites" and nephelite basanites occur. The basalts show some variation, but there are the two usual main types, one porphyritic, with labradorite phenocrysts, and the other densely aphyric. The texture is ophitic, the plagioclase and augite are as usual, there is a little olivine, and sometimes a little glass. An average of 13 analyses is given in Table IX. The lower iron oxides and lime and the higher alkalis show the decided alkalic affinities of the basalts.

We have little information as to the rocks of *Franz Josef Land* and but two analyses of them.³⁰ The basalts are aphyric for the most part, but some are porphyritic, with labradorite phenocrysts, and Teall describes one with augite phenocrysts. The mode is the usual one of the plateau basalts, but a little olivine is present in a few specimens. Although the texture is generally ophitic, yet this is not so common as among the basalts of Iceland and the Faroes, as was pointed out by Teall. Many of Teall's specimens contain glass. The average of the two analyses available is given in Table IX.

The *chemical characters* of the Thulean basalts are shown in a series of averages for the various districts given in Table IX. These averages are of the basalts alone and do not include any analyses of rhyolites or other non-basaltic rocks.

TABLE IX
Averages of Analyses of Thulean Basalts

	1	2	3	4	5	6	7	8
SiO ₂	46.54	48.64	49.04	45.80	45.08	49.05	48.09	47.46
Al ₂ O ₃	14.96	14.05	13.54	13.32	14.15	13.47	13.77	13.89
Fe ₂ O ₃	4.34	3.03	2.43	5.12	2.28	3.27	4.58	3.58
FeO	9.07	9.96	10.46	9.46	8.59	9.15	9.05	9.38
MgO	7.29	5.26	7.42	6.34	7.01	8.16	6.03	6.79
CaO	9.25	9.92	10.55	9.64	10.20	8.22	11.04	9.83
Na ₂ O	2.84	3.06	2.43	2.39	3.99	3.11	2.47	2.90
K ₂ O	0.78	0.75	0.53	1.36	1.79	1.50	0.39	1.01
H ₂ O±	2.69	1.04	0.67	2.00	0.90	0.89	2.15	1.48
TiO ₂	2.15	3.78	2.51	3.84	2.93	1.89	1.89	2.71
P ₂ O ₅	0.21	0.38	0.38	0.34	0.62	0.84	0.24	0.43
MnO	0.29	0.18	0.20	0.18	0.22	0.18	0.29	0.22
Incl.	0.10	....	0.19	0.31	2.68	0.03	0.08	0.22
	100.51	100.05	100.35	100.10	100.44	99.76	99.67	99.90

²⁹ H. Backlund: Tsch. Min. Pet. Mitth., vol. 26, 1907, p. 357; A. Hamberg: Geol. For. Forh., vol. 21, 1899, p. 509; V. M. Goldschmidt: Skr. Videns. Selsk. Christ., 1911, no. 9; Holmes and Harwood: Min. Mag., vol. 18, 1918, p. 205.

³⁰ J. J. H. Teall: Quart. Jour. Geol. Soc., vol. 53, 1897, p. 477, and vol. 54, 1898, p. 646; Holmes and Harwood: Min. Mag., vol. 18, 1918, p. 209.

1. Hebrides, etc.; 7 analyses.
2. Faroes; 2 analyses.
3. Iceland; 5 analyses.
4. Greenland; 3 analyses.
5. Jan Mayen; 1 analysis.
6. Spitzbergen; 13 analyses.
7. Franz Josef Land; 2 analyses.
8. Average of Thulean basalts.

As Holmes remarks, "the outstanding features of the Arctic (Thulean) basalts are low silica, alumina, and alkalies and high titanium dioxide, iron oxides, and lime." They thus show the main chemical features of the Deccan and Oregonian basalts; but it is to be noted that the total amounts of iron oxides are rather lower than in the last, while there is a somewhat greater amount of ferric oxide relative to ferrous, this being due possibly to the slightly altered condition of some of the specimens. The excellent analyses by Harwood are of great value in showing the general presence of notable and constant amounts of chromium and vanadium, which is corroborated by the figures by Pollard and Radley for Scottish basalts and those of Dittrich for chromium in Spitzbergen basalts. The percentage of titanium dioxide is generally very high, and Holmes devotes considerable space to discussion of the inverse variation between titanium and the feldspars.

It is scarcely necessary to give here the norm of each of the average analyses above, so that only the norm of the general average of the Thulean region is shown here.

TABLE X

Norm of Thulean Basalts

Quartz	0.84
Orthoclase	5.56
Albite	23.06
Anorthite	23.91
Diopside	18.14
Hypersthene	12.86
Magnetite	5.57
Ilmenite	7.45
Apatite	1.01

Symbol III.5. (3)4.4.

The close general correspondence between this norm and those of the Deccan and Oregonian basalts will be evident at a glance. We see the same tendency toward an excess of silica, in spite of the general Thulean rather lower silica and nephelinitic affinities, the approximately equal

amounts of normative albite and anorthite, the almost negligible amount of orthoclase, the approximately equal amounts of diopside and hypersthene, and the high magnetite and ilmenite molecules.

SIBERIAN BASALTS

In central Siberia is a very large, and as yet imperfectly known, area of basaltic rocks, which, although not everywhere continuous, occur as extensive horizontal sheets, forming either flows or intruded sills. The name Siberian traps has been given to this complex by Russian geologists. The main and central areas are mapped by Ahlburg³¹ (figure 2), but according to Suess³² and Backlund³³ they have a much wider extension than



FIGURE 2.—Sketch Map showing the main central Area of the Siberian Basalts
(From Ahlburg.)

shown by Ahlburg. Outliers occur northward to the Arctic Ocean, from the mouth of the Yenisei eastward as far as the De Long and New Siberian Islands (possibly beyond) and inland nearly to Bering Sea. Suess and Backlund comment on the similarities between these Siberian basalts and those of the North Atlantic (Thulean) region and suggest—Back-

³¹ J. Ahlburg: *Zeits. prakt. Geol.*, vol. 21, 1913, p. 108, and figure 1.

³² Suess: *The face of the earth* (English translation), vol. 3, 1908, pp. 20-38.

³³ H. G. Backlund: *Mem. Acad. Sci. St. Petersburg*, vol. 21, no. 6, 1910; and *Acta Acad. Abo.*, vol. 1, 1920. p. 1.

lund doubtfully—that they are parts of the same province. Holmes also includes basalts from Kuszkin Island, at the mouth of the Yenisei, with his Brito-Arctic basalts. On the whole, however, in view of the paucity of our knowledge of them, the vastness of the area covered by these flows and their eastward extension, the peculiar tectonic features as described by Suess and Backlund, and the intervention of Nova Zembla and the Samoyed Urals (virgate extensions of the Ural Mountains), it seems best to consider this Siberian basaltic area as distinct from the Thulean.

According to Suess:

“These mighty Siberian flows have in all likelihood a common origin. In some places at least their extrusion has persisted up to very recent times, but the date of their first appearance is unknown. Nowhere is a volcano of any importance to be seen. The presence of small ash cones tends rather to confirm than to refute the view put forward in recent times, that these great flows do not take place from isolated throats, but from a network of fissures.”

So little is known of these basalts petrographically that a few words must suffice for their description. According to Chrustschoff³⁴ and Ahlburg,³⁵ the basalts of the main central areas are of fairly uniform character. They are rather coarse grained, composed largely of labradorite and enstatite-augite, sometimes with and sometimes without olivine, and some of them with much glass. The holocrystalline forms are ophitic. The basalts from the eastern part of Siberia, according to Backlund's descriptions and analyses by Sahlbom, are decidedly more alkalic, some of them being called trachydolerite and others nephelinite. Backlund notes the very late period of crystallization of the magnetite. The analyses of true basalts from this vast region are so few or so imperfect that it seems to be scarcely worth while to quote them here. So far as they go, they indicate general chemical characters in harmony with those of the better known plateau basalts, although the iron oxides do not seem to be quite as high.

In connection with the Siberian and the previously described Thulean basalts, it is worth noting that von Wolff³⁶ considers that these and other such vast areas of basaltic lavas can not be referred to either the Atlantic or the Pacific clans of Harker and Becke. He proposes the recognition of a clan, of equal rank with the other two, which he calls the “Arctic” and whose chief chemical characters are those of these plateau basalts and their differentiation products. He suggests that the charnockite-anor-

³⁴ K. von Chrustschoff: *Bull. Acad. Imp. Sci. St. Petersburg* (2), vol. 34, 1892, pp. 193-224.

³⁵ J. Ahlburg: *Zeits. prakt. Geol.*, vol. 21, 1913, p. 108.

³⁶ F. von Wolff: *Der Vulkanismus*, vol. i, 1914, p. 153.

thosite series of Rosenbusch belongs with the Arctic clan, but reasons have been adduced elsewhere³⁷ to show that this conjecture is unjustified.

PATAGONIAN BASALTS

Scattered through Argentine Patagonia, from the Rio Negro to Tierra del Fuego, are numerous areas of plateau basalts.³⁸ These form thick horizontal sheets, covering the sedimentary rocks, and have a total area of "many thousands of square miles." They would seem to have been first noted by Darwin during the voyage of the *Beagle*, and he attributes their origin to Andean volcanoes. Both Hauthal and Hatcher, however, point out that they have originated from numerous fissures and (according to Hatcher) many cones, and they must have been very fluid. Both Suess and von Wolff reckon them among the plateau basalts. Their age is uncertain, but they would seem to be late Tertiary and some of them much more recent.

These lavas are spoken of as basalts by all who have written about them, but there are no petrographic descriptions of them and no analyses. In order to try to obtain some information along these lines, I endeavored through the kindness of Prof. C. H. Smyth, Jr., to obtain some of Hatcher's specimens. It seems, however, that no specimens of these basalts collected by Hatcher are to be found in the collections at Princeton, and apparently he brought none back with him. Professor Smyth, however, found a few specimens of basalt obtained from Ameghino, which he very kindly entrusted to me for study. These specimens are all small fragments, none of them very fresh or compact, and without any definite locality noted on the label. Unsatisfactory as they are, however, it was thought that study of them might be of interest, in view of the almost total absence of knowledge concerning these basalts, and I would express my thanks to Professor Smyth for his kindness in furnishing the material.

The specimen selected for study was what appeared to be the freshest and was stated to have come from "la base des couches à *Notostylops*," Patagonia. The rock, megascopically, is a dense, compact, aphyric, slightly brownish black basalt. In thin section it shows the usual sub-

³⁷ Cf. H. S. Washington: The charnockite series of igneous rocks. *Amer. Jour. Sci.*, vol. 41, 1916, p. 338.

³⁸ Cf. Darwin: *Geological Observations*, 2d ed., 1891, pp. 381-384; J. B. Hatcher: *Amer. Jour. Sci.* (4), vol. 4, 1897, p. 350; R. Hauthal: *Peterm. Mitth.*, 1903, pp. 97-102, map 9; J. B. Hatcher: *Princeton Univ. Exped. to Patagonia*, vol. i (narrative and geography), 1903, *passim*, and especially pages 109, 218-221, and 287; Suess: *Face of the earth*, vol. iv, 1909, p. 485; F. von Wolff: *Vulkanismus*, vol. i, p. 432, 1914. Some of the western areas are mapped by P. Quensel; *Bull. Geol. Inst. Upsala*, vol. xi, 1911.

ophitic texture, being composed of tabular labradorite crystals, with interstitial grains of a slightly brownish augite, some thin plates of ilmenite (?), very few equant magnetite grains, and considerable brownish interstitial glass. There are a few automorphic, but somewhat corroded, crystals of olivine which is partially serpentinized. The thin section much resembles those of some of the Deccan traps, especially that of the olivine basalt of Nasik in Bombay.

TABLE XI
Analysis of Patagonian Basalt

	1	2
SiO ₂	48.36	50.74
Al ₂ O ₃	12.01	12.60
Fe ₂ O ₃	4.56	4.78
FeO	6.91	7.25
MgO	8.58	9.00
CaO	8.48	8.90
Na ₂ O	2.47	2.59
K ₂ O	0.69	0.72
H ₂ O+	2.76	....
H ₂ O—	1.46	....
TiO ₂	2.60	2.73
P ₂ O ₅	0.35	0.37
MnO	0.30	0.31
	99.53	99.99

A chemical analysis gave the results shown in Table XI, there being given also in number 2 the figures for the major constituents reduced to 100 per cent after omission of water, as the content in water is inordinately high. It will be seen that the analysis resembles in general those of other plateau basalts, except that the total iron oxides are somewhat lower (even when the water content is eliminated), with ferrous oxide not so highly dominant over ferric as in most of them and with magnesia decidedly higher. The percentage of manganese is rather high, but those for titanium and phosphorus oxides are about normal. It will be noted that here, as was the case with the olivine basalt of Nasik, there is a very decided excess of silica shown in the norm, as given below. This crystallization of olivine in a magma that has excess silica, like that of the Nasik basalt mentioned above, is in harmony with Bowen's³⁹ experimental observations of the early crystallization of olivine and its later resorption and the subsequent crystallization of enstatite.

³⁹ Bowen and Andersen: Amer. Jour. Sci., vol. 37, 1914, p. 496; N. L. Bowen: Amer. Jour. Sci., vol. 38, 1914, p. 235.

TABLE XII

Norm of Patagonian Basalt

Quartz	3.54
Orthoclase	3.89
Albite	20.96
Anorthite	19.74
Diopside	15.44
Hypersthene	19.20
Magnetite	6.73
Ilmenite	5.02
Apatite	1.01

Symbol III."5.3".4(5).

This norm resembles closely those of most of the other plateau basalts which we have studied, especially in the notable quartz (excess silica), the almost equal amounts of albite and anorthite among the salic minerals and of diopside and hypersthene among the femic, and the comparatively large amounts of magnetite and ilmenite. This correspondence with the others is concisely brought out by the symbol.

As to the Patagonia basalts, it may be said in general, so far as we may judge from the single specimen examined, that they show in their chemical and modal features the chief characteristics of the plateau basalts. We have already briefly noted that their occurrence also shows the typical plateau basalt features, namely, horizontality and great extent of a series of many sheets, which attain to very considerable total thickness, these features indicating a state of great fluidity at the time of extrusion. That they issued from fissures, at least in great part, is shown by Hauthal's observations and in part by those of Hatcher. The testimony of the latter, who was essentially a paleontologist and was so little interested in the basalts that he failed to bring back specimens, may be held as of less weight than that of Hauthal, who made a special study of the structural features of the whole region.

ALGONKIAN AND PALISADAN REGIONS

In order to render our survey of plateau basalts more nearly complete, two regions in the United States may be mentioned; they are so well known that lengthy description is uncalled for here. One of these is the area of igneous rocks, of Keweenawan age, around Lake Superior. Following a suggestion of Prof. A. C. Lane, I have named this the Algonkian region.⁴⁰ The other is the long series of Triassic sills and flows which

⁴⁰ H. S. Washington: Bull. Geol. Soc. Amer., vol. 33, 1922, p. 380.

extends from Nova Scotia to South Carolina, east of the Appalachians. This may be called the Palisadan region, after J. D. Dana's old appellation, the Palisade Mountains, for the series of block ranges belonging to the Newark System.⁴¹

In their general characters—physical, petrographical, and chemical—the igneous rocks of these regions resemble very closely those of the regions already described. The flows have issued from fissures, with little or no explosive, cone-building activity; the sheets are, or originally were, horizontal and of great areal extent, and the aggregate thickness of the series of sheets is very great.

The rocks are predominantly basaltic, either intrusive sheets of diabase or surface flows of basalt, with ash beds in small amount. Rhyolitic flows accompany the Algonkian basalts, but these appear to be generally absent in the Palisadan region. The basalts are composed very largely of augite and labradorite, in more or less equal amounts, with small amounts of magnetite and apatite. The augite would appear to be, at least in the Palisadan region, an enstatite-augite similar to that of the Deccan and Thulean regions. A little quartz is frequently present, in some of the Palisadan diabases rising to such quantity as to justify the name quartz diabase for the rock, and frequently forming (with feldspar) interstitial micropegmatitic patches. On the other hand, olivine is not uncommon, and this again is sometimes so abundant as to justify the names olivine diabase or olivine basalt. Glass is frequent in the Palisadan basalt, and it is noteworthy that, according to the excellent descriptions of Lewis, as the glass content increases, the amount of augite and magnetite decreases, definite magnetite crystals being replaced by "dust" or minute dendritic growths, just as we have seen to be the case with the Deccan basalts. In megascopic texture these basalts are very uniform and the type with abundant feldspar phenocrysts is very rare, in contrast with the other plateau basalts, while phenocrysts of augite or olivine appear to be more common.⁴²

Chemically the Algonkian and Palisadan basalts and diabases greatly resemble those of the Deccan, Oregonian, and Thulean regions. Good analyses of the Algonkian rocks are not numerous, and many of them appear to be of not very fresh specimens. The Palisadan diabases show considerable variation, the silica in the analyses given by Lewis (page 121) varying from 60.05 to 49.02, while the basalts are much more uniform.

⁴¹ Cf. J. D. Dana: *Manual of Geology*, 4th ed., 1895, p. 357.

⁴² The literature on the petrography of the Algonkian and Palisadan basalts is so extensive that it can not be cited here. For the Algonkian rocks reference may be made to Lane, and for the Palisadan rocks to J. V. Lewis: *Geol. Survey New Jersey, Ann. Rept.* for 1907, 1908, pp. 99-167.

An average of eight analyses of New Jersey Palisadan basalts is given in Table XIII. These basalts, both Algonkian and Palisadan, do not show the very high percentages for the iron oxides which we have found in the Deccan and other plateau basalts, but they would appear to be higher than the average of ordinary basalts. We see in the average norm an excess of silica, which is characteristic of plateau basalts, and the similar approximately equal amounts of albite and anorthite, and of diopside and hypersthene.

No more than mention may be made here of the Stormberg plateau basalts of the Karroo system, in South Africa. It is hoped soon to undertake a study of them, in conjunction with Dr. Fred E. Wright, who has recently returned from the region with many specimens.

TABLE XIII

Averages of Plateau Basalts

	1	2	3	4	5	6
SiO ₂	50.61	49.98	47.46	50.74	50.66	48.78
Al ₂ O ₃	13.58	13.74	13.89	12.60	14.28	15.85
Fe ₂ O ₃	3.19	2.37	3.58	4.78	3.41	5.37
FeO	9.92	11.60	9.38	7.25	8.58	6.34
MgO	5.46	4.73	6.79	9.00	6.92	6.03
CaO	9.45	8.21	9.83	8.90	8.60	8.91
Na ₂ O	2.60	2.92	2.90	2.59	2.92	3.18
K ₂ O	0.72	1.29	1.01	0.72	0.72	1.63
H ₂ O±	2.13	1.22	1.48	....	2.28	1.76
TiO ₂	1.91	2.87	2.71	2.73	1.30	1.39
P ₂ O ₅	0.39	0.78	0.43	0.37	0.17	0.47
MnO	0.16	0.24	0.22	0.31	0.12	0.29
	100.12	99.95	99.78	99.99	99.96	100.00

1. Deccan basalts; 11 analyses.
2. Oregonian basalts; 6 analyses.
3. Thulean basalts; 33 analyses.
4. Patagonian basalt; 1 analysis.
5. New Jersey basalts; 8 analyses.
6. Daly's average basalt.

CONCLUSIONS

CHARACTERS OF PLATEAU BASALTS

We may now summarize the general characters of the plateau basalts. Structurally, they have characteristically issued from fissures, although this quiet extrusion is sometimes accompanied by minor explosive activity. They form horizontal flows of very great extent, indicating a high degree

of fluidity at the time of extrusion. The flows are individually of considerable thickness and the total thickness of the series of superimposed flows is very great. Ash beds and layers of scoria are not abundant. In several regions the basalts are associated with flows of rhyolite or toscanite, while accompanying andesite and trachyte are rarely met with, and lenadic lavas, such as phonolite or tephrite, seldom or never occur. They have been extruded at very different geological epochs, from the pre-Cambrian to recent times.

Megascopically, they are very dark, black or occasionally brownish black, rarely dark gray. In granularity they may vary from rather coarsely doleritic to densely aphanitic, some few being evidently highly vitreous. Vesicular forms seem to be rare as compared with ordinary basalts of volcanic cones. The great majority are aphyric, but there is some tendency to a porphyritic development of the feldspar, especially in the Thulean region, forming a special textural type. Augite seldom forms megaphenocrysts, and these small and sparse, while olivine phenocrysts are very rarely present, except in some of the Algonkian and Palisadan diabases.

Thin sections show a striking uniformity in mode, or at least in general mineral composition. Augite and a labradorite (generally about Ab_1An_2) make up about 90 per cent of the rock in most cases, and in all these two minerals form much the greater part; both are present in approximately equal amounts, although there may be some variation in the preponderance of the one or the other. The augite is colorless or, more generally, slightly brownish, and seems to be commonly an enstatite-augite in all the regions—that is, the hypersthene molecule is present in the pyroxene in amount about equal to that of the diopside molecule. This is in strong contrast with common basaltic augites, such as the loose crystals at Etna, Stromboli, Vesuvius, the Alban Hills, and Haleakala, which are dominantly diopsidic. The augite is almost always interstitial, and consequently anhedral—a point to be mentioned later.

The plagioclase offers no features of special interest, except that it is practically always tabular and euhedral or subhedral. The ordinary twinning lamellæ are always present, zonal structure is rare or absent, and it carries almost no inclusions. Orthoclase is seldom present; so that the molecule of this must exist in solid solution in the labradorite. In the typical plateau basalts—indeed, in all the specimens studied by me—no nephelinite is present, although some nephelinite basalts or tephrites accompany the normal basalts in a few places, as in the Thulean and Siberian regions.

Olivine is generally rare, except in the Algonkian and Palisadan re-

gions; in the typical Deccan and Oregonian basalts it is but sparingly present in a few specimens. Neither hornblende nor biotite seems to be present as a normal constituent in any of the regions.

Quartz is not usually present in these basalts, although many of them show an excess of silica in the norm. It occurs in many of the Palisadan diabases, however, in micropegmatitic patches interstitial between the pyroxene and the feldspar. Magnetite is common in all the holocrystalline plateau basalts and in decidedly large amount. Its quantity diminishes, however, with increase in the content of glass. This is the rule in my specimens of the Deccan and Oregonian basalts and is also true of the Thulean and Palisadan basalts, to judge from the descriptions of Holmes and Lewis respectively. The magnetite is evidently highly titaniferous, and ilmenite is present in many of the basalts, forming thin plates. Apatite is common in the usual small prismoids, and calls for no comment.

In crystallinity the plateau basalts vary from entirely holocrystalline to quite vitreous forms. The amount of glass may vary from none to about 25 per cent, rarely more, and small, local occurrences of almost holohyaline basalts may occur. The glass is either colorless or so crowded with "dust" that it often appears to be opaque, or is yellow. The content in augite, and still more in magnetite, decreases with increase in the amount of glass, pointing to the conclusion that these two minerals are the last to crystallize, and that the glass has the general composition of a mixture of augite and magnetite.

The microtexture is most often ophitic, the thin tables of labradorite lying in an interstitial mass of anhedral augite grains. Less often it is intersertal, and still less often is a typical "basaltic" texture shown. Textural evidence of flow is seldom seen.

Chemically, the plateau basalts differ materially from other basalts in one or two features. In Table IX are given the averages of analyses of basalts of various regions, with the average basalt as computed by Daly from 161 analyses of basalts so named by the authors.⁴³

The averages of the three most typical plateau basalt regions—the Deccan, Oregonian, and Thulean—are closely alike. The percentages of silica, alumina, lime, alkalies, phosphorus, and manganese oxides are quite like those in the volcanic cone basalts, although both soda and potash are slightly lower. Magnesia is distinctly lower, except in the Thulean region and in the one analysis of a Patagonian basalt. The chief difference is seen in the much higher amount of iron oxides, with ferrous oxide greatly preponderating over ferric oxide. In the typical

⁴³ R. A. Daly: *Proc. Amer. Acad.*, vol. 45, 1910, p. 224.

plateau basalts the combined iron oxides would amount to about 14 per cent or more, and this is the more marked if only the most abundant group of the more femic basalts are considered. I am inclined to think that the comparatively high ferric oxide shown in Daly's average is due in part to oxidation of ferrous oxide through slight alteration and in part to defective determination of the ferrous oxide—a not unusual analytical error. The percentage of titanium dioxide is appreciably high in the plateau basalts.

It would thus appear that the plateau basalts differ from what might be called the cone basalts essentially in the higher iron and titanium content of the former and possibly in the relatively less oxidized condition of the iron. This must be considered as a broad general distinction. Examples may be found among typical plateau basalts in which the iron oxides are not specially high, just as examples may be found among cone basalts in which the iron oxides are much higher than the average. Mineralogically, as we have seen, this chemical difference is expressed in the presence of highly ferromagnesian hedenbergitic enstatite-augite in the plateau basalts, in contrast to that of highly calcic or diopsidic augite in the cone basalts. It may also find expression in the striking tendency of the augite and magnetite to be among the last minerals to crystallize; so that the glass present in the not wholly crystallized plateau basalts would have a composition corresponding to a mixture of augite and magnetite, examples of which we have seen on the island of Skye, in Colorado, and possibly elsewhere.

CLASSIFICATION OF BASALTS

It would follow from the considerations just mentioned that basalts, in general, may be referred to at least two different groups: the plateau basalts, which are high in iron, and the cone basalts, which are low in iron and relatively high in magnesia and lime. This does not preclude, it must be said, the possibility of the recognition of other groups of basalts, such as, let us say, those high in soda and grading into nephelite tephrites, or those high in potash and grading into leucite tephrites.

No hard and fast line can be drawn. As Iddings showed many years ago and as continued and continuous study of igneous rocks has abundantly proved to be the case, igneous rocks grade into each other in all possible ways. We are not dealing in the classification of rocks, with more or less definitely classifiable separate individual entities, as is true of plants and animals, in which the individual records the progress and the direction of evolution, and the characters of which are brought about very largely through the necessity for the means of adaptation of exist-

ence (by feeding) and preservation of the race (through procreation) to the conditions of the environment. In rocks, on the contrary, we deal, not with sharply discrete individuals and groups of individuals, but with indefinite mixtures, which grade or shade into each other in every (chemical, mineral, and textural) direction. At the best, we may conceive of and concentrate our attention on certain somewhat vague and ill-defined centers around which the igneous rocks cluster, much as a nebula, spiral or otherwise, may cluster about a nucleus, the outer limits of both the nucleus and the nebula being hazy and strictly indeterminate. There is no individual *rock species*, as there is an animal or vegetal species, indeterminate, transitional, and transitory as such an organic species may be.

It would follow from the considerations just expressed that there can probably be no exact definitely determinable or definable classification of igneous rocks, such as we find in zoology and botany. We can classify rocks, for petrological purposes, exactly, definitely, and strictly only by creating arbitrary divisions, cutting them up by sharp planes and putting them into man-devised pigeon-holes, as was done in the quantitative classification or as seems to be necessary in any modification of it. Such a classification is a pis-aller, a makeshift, a classification of convenience; it may or may not correspond to the evolution of igneous rocks as it really is. That is for the future to determine. Personally, I doubt that an exact petrological classification of igneous rocks can ever be attained. We may arrive at some sort of approximation to an orderly arrangement for purposes of petrographic description and petrological discussion, which might by courtesy be called a classification; but in the attainment of a classification *sensu stricto* we shall be apparently always restricted by the inherently indeterminate characters of the things which we attempt to classify, the igneous rocks.

The prevalent belief in the possibility of the reference of igneous rocks or comagmatic regions to a few definitely delimited groups is seen in the conception of the so-called Atlantic and Pacific families of Harker, Becke, and others. Apart from the now fairly obvious misapplication of the names, there is evident throughout the literature dealing with them the assumption that rocks or rock magmas may be referable to only two great chemico-mineral groups. The attempts to reconcile this dualistic idea with the actual occurrence of igneous rocks and comagmatic regions are often futile, if not sometimes ludicrous.

Von Wolff⁴⁴ was evidently struck by some of the difficulties inherent in such a limited interpretation when he proposed that the plateau basalts

⁴⁴ F. von Wolff: *Der Vulkanismus*, vol. i, 1914, p. 153.

of the Thulean and Siberian regions, and by implication those of the Deccan, Oregonian, Algonkian, and Palisadan regions, should be considered as representing a distinct group, which he calls the Arctic, of the same general classificatory rank as the Atlantic and the Pacific rocks. With this suggestion von Wolff unconsciously shatters the dualistic conception of igneous rocks, which comes down to us from Bunsen's study of the Iceland lavas, and from even farther back in the early human tendency to a dualistic interpretation of nature, as seen in night and day, good and evil, Ormuzd and Ahriman. In studying igneous rocks we can not limit ourselves to dualism; but, even assuming a possibly monistic origin in the primordial magma, we must turn to a polyistic concept of their relations. We must consider rocks as derived from or referable to not only two lines of descent, but as coming down to us either from a heterogeneous, diversified, or from a possibly single homogeneous earth magma along many lines which may, and we have reason for thinking do, intertwine or even throw back atavistically in their course of physico-chemical evolution, one phase of which we call differentiation. On a small scale this diverse evolution is seen in the glass and the holocrystalline parts of, let us say, the Deccan basalts or in the border and the interior of a composite dike; on a large scale it is seen in the different comagmatic regions or, still more broadly, in the petrologic difference between the continental masses and the ocean floors.

This last may seem to lead us inevitably to the usual dualistic idea of the division of a primordial magma along two lines, ending in the two extremes of a "basaltic" and a "granitic" zone or stratum, according to the theory of so-called gravitative adjustment, as first propounded by Darwin and later by Daly and others. In reality, however, the course of differentiation would seem to be not so simple, but to have given rise to various chemically and consequently minerally quite diverse side lines, much as we see to have been the case in organic evolution. We meet with an overwhelming preponderance of granite and rhyolite, diorite and andesite, gabbro and basalt, with all their various varieties, subvarieties, and shades of subvarieties. But, large as may loom these common, universal rocks, we must not forget the *rare aves* of petrography, such as the ilmenite-apatite rock nelsonite, the albite-rutile kragerite, or the magnetite basalt arapahite, which, for the study of rock genesis, rock evolution, or rock classification, may be of importance equal to the vastly greater and more numerous masses of the familiar rocks mentioned above; much as the comparatively rare *Peripatus* and the *Cycadaceæ* are of some special interest in the study of the phylogeny of animals and plants.

CAUSE OF FLUIDITY

The preceding descriptions of the plateau basalts, showing that one of their main chemical characteristics is the high percentage of iron oxides, and especially of ferrous oxide, furnish an explanation of their great fluidity at the time of extrusion. It is a matter of common observation that basalts generally are fusible at a lower temperature, and are more fluid when molten, than are more feldspathic or more silicic rocks. It is also well known that ferrous silicates are more readily fusible than are magnesium or calcium silicates. The experience of iron and steel workers and smelters bears testimony to the lower fusibility and greater fluidity of slags containing considerable iron. This is the opinion expressed to me orally by Mr. J. A. Aupperle, of the American Rolling Mill Company, and Dr. W. G. Fearnside, of Sheffield. In a recent letter Mr. Aupperle communicates the conclusions arrived at in the works of the American Rolling Mill Company; these are so pertinent that part of his letter may be cited:

"From our observations we firmly believe that the higher the iron oxides in slags the more fluid these slags will be, as we have noticed that the slag from Armco Ingot Iron, which contains the highest iron oxide, is extremely fluid. When high iron oxide slag . . . is poured on the ground in large masses it freezes immediately to a very compact mass, while slags containing lower iron oxide form porous masses and are not so homogeneous. The slags in the slag pockets of our open-hearth furnaces are also high in iron oxide, and they are likewise very fluid."

The same general relation is expressed in papers on iron slags by J. H. Whiteley.⁴⁵ Inasmuch as the fissure eruptions which furnished the plateau basalts show slight explosive activity, it is to be inferred that the magma contained comparatively little gas, so that the effect of this class of components in lowering the fusing point or increasing the fluidity should be less than in ordinary basalts of the explosive cone type. We seem, therefore, to be justified in ascribing the peculiar physical condition of these basalts during their extrusion chiefly to their high iron content.

⁴⁵ J. H. Whiteley and A. F. Hallimond: *Jour. Iron and Steel Inst.*, vol. 99, 1919, p. 199; and J. H. Whiteley, *op. cit.*, vol. 101, 1920, p. 308.

SOME NEW FACTS BEARING ON CORRELATIONS OF
CHESTER FORMATIONS¹

BY E. O. ULRICH

(Read before the Paleontological Society December 30, 1921)

CONTENTS

	Page
Introduction.....	806
General statement.....	806
Miscorrelations of the Cypress sandstone.....	806
The 1905 report on western Kentucky.....	808
Ulrich's 1905 subdivisions of the Chester.....	808
Publications on Chester formations in past decade.....	810
Matters in controversy with Professor Weller.....	811
The report on Hardin County, Illinois.....	813
The locality near Levias, Kentucky.....	815
Comparisons as to relative abundance and quality of evidence.....	818
Chester types in the Fredonia fauna.....	819
The Upper Ohara fauna.....	820
Occurrences of <i>Platycrinus</i> , <i>Dizygocrinus</i> , and <i>Pugnoides</i> in the Upper Ohara.....	821
Field investigations in 1921.....	823
Review of itinerary.....	823
Lower Chester section in Sainte Genevieve County, Missouri.....	825
General statement.....	825
A marine fauna in the Aux Vases sandstone.....	828
Fauna in top shale of Sainte Genevieve limestone.....	829
Lower Chester section in Union County, Illinois.....	830
Difficulties in correlating the Union County section.....	831
The fauna of Bed IX of the section in Union County, Illinois	833
Unquestioned Paint Creek beds in the Union County section.	836
The section in Hardin County, Illinois, and Crittenden County, Kentucky.....	837
The section in Caldwell and Christian counties, Kentucky.....	837
The sections in southeastern Kentucky and northern Alabama...	839
Local occurrence of crinoid colonies.....	840

¹ Manuscript received by the Secretary of the Society June 7, 1922.

Published by permission of the Director of the U. S. Geological Survey.

	Page
Upper Ohara fossils in Sainte Genevieve limestone south of Somerset, Kentucky.....	843
The section near Huntsville, Alabama.....	844
Species and geographic distribution of the Upper Ohara crinoid fauna.....	847
Age of the crinoid bed near Burksville, Illinois.....	848
Conclusions.....	851

INTRODUCTION

GENERAL STATEMENT

It is with regret and aversion that I return to the discussion of a subject on which I had hoped my last word had been written four years ago. Indeed, I would not do so if it were merely to continue the "Chester controversy" that began ten years ago, when Prof. Stuart Weller submitted a manuscript report on stratigraphic investigations in western and southern Illinois carried on by him under cooperative arrangements between the U. S. Geological Survey and the Illinois Geological Survey.

The author of the manuscript refused to accept my classification of the Chester series² because he found it inapplicable to the Illinois section and erroneous in certain important respects. Following epistolary discussion of the disputed matters, we spent about a week of 1913 in a rapid review of the concerned areas in Illinois and Kentucky, accompanied by Mr. H. A. Buehler and Mr. Frank W. De Wolf, the State Geologists of Missouri and Illinois respectively.

This field conference proved me in error in correlating the main body of Chester limestone in Randolph County, Illinois, to which Weller subsequently applied the name Okaw limestone, with the Kentucky formation which I had described under the term Tribune limestone. It was found that the Okaw limestone is the younger of the two. We found also that the limestone at Tribune, in Crittenden County, Kentucky, is not at all the formation that I had in mind and described under that name from outcrops in Caldwell and Christian counties. But this conclusion merely corroborated what I had learned about the limestone at Tribune two or three years before 1913.

MISCORRELATIONS OF THE CYPRESS SANDSTONE

However, the main reason for our 1913 field conference concerned the age of the massive sandstone at Rosiclare, Illinois, and at various places

² U. S. Geol. Survey, Prof. Paper 36, 1905.

in Crittenden and Caldwell counties in Kentucky which Engelmann had identified as Chester Bed number 8 of his classification of the Chester in Johnson County, Illinois. Weller contended that this sandstone is of Pottsville age and not Chester at all, a view in which he could not be shaken until in 1915, when through his own investigations he finally satisfied himself that it lies in the lower half of the Chester group.

In 1863 Engelmann applied the name Cypress sandstone to his Chester Bed number 8, and, as stated, he identified number 8 in the bluff just below Rosiclare. In 1905 I resurrected this name—Cypress—and, starting with the bluff section at Rosiclare, applied it on the south side of the Ohio, consistently and without a single serious error, across the exceedingly faulted area comprised in the Kentucky counties of Livingston, Crittenden, Caldwell, and Christian. I did not know that Engelmann had been in error in determining the sandstone capping the bluff below Rosiclare as the same bed that he had called Cypress sandstone in Johnson County. Indeed, there was no valid reason to doubt Engelmann's determination, and consequently none also concerning the sandstone mapped in Kentucky under the name Cypress until 1915, when Butts found that the great sandstone bluff along the Ohio in Pope County, Illinois, is in fact composed of three parts, namely, a lower sandstone which is the same as the one in Downey's Bluff at Rosiclare, an upper sandstone, now known to correspond to the true Cypress sandstone of Johnson County, and between the two sandstones an important, but here thin, shale formation.

Although the discovery of these relations at once invalidated my 1905 usage of the term Cypress, I do not admit that it corrected any grievous error on my part. I had no reason to doubt, and therefore accepted, Engelmann's identification of the Cypress sandstone at Rosiclare as correct. Besides, Engelmann, also Worthen, had regarded the Chester Bed number 8—in other words, the Cypress sandstone—as corresponding to the Ferruginous sandstone, or, as now known, the Aux Vases sandstone, of the Mississippi Valley. I, too, had studied the section in the Mississippi Valley and, basing my conception of the Cypress on what I saw in the bluff at Rosiclare, I agreed with Engelmann and Worthen, and accordingly recognized Cypress as the oldest of the geographic names and placed the terms Ferruginous and Aux Vases as synonyms under it. Had I, like Engelmann, confused or combined the two sandstones in Kentucky, I would feel more culpable. But I did not, and the error into which I fell in this case is a nomenclatural one almost solely. It does not affect the sequence of formations in Kentucky; we merely transfer the name to a higher sandstone and either use Aux Vases for the lower

sandstone or give it a new name, as has been done by Butts, who called it Bethel sandstone.

I feel much greater responsibility in the case of the misapplied term Tribune. But these and one or two other less important lapses are conceded and corrected in my part of the work on "Mississippian Formations in Western Kentucky," by Butts and Ulrich. They are past history and worthy of recollection only as illustrations of the danger of relying on the testimony of others. Had I gone to Cypress Creek, Engelmann's type locality, the name Cypress sandstone would not have been misapplied by me. Again, if I had studied the outcrop of limestone at Tribune instead of relying on the report of an assistant, doubtless some other more appropriate term than Tribune limestone would have been found for the perfectly good formation to which Butts subsequently gave the name **Gasper limestone**.

THE 1905 REPORT ON WESTERN KENTUCKY

In U. S. Geological Survey Professional Paper 36 I made my first effort to divide the Chester group into formational units and subordinate members and beds. The composite result of this attempt, as determined by combination of various tables and statements in the cited publication, particularly on pages 24, 38, and 61, and the stratigraphic relations of the several units to those recognized in the generalized classification of the Upper Mississippian formations now generally recognized are as shown in the following table:

ULRICH'S 1905 SUBDIVISIONS OF THE CHESTER

The following are my subdivisions of the Chester in Crittenden and Caldwell counties, Kentucky, in 1905, correlated with present classification:

Chester group or series	Birdsville formation		Bed 12	Kincaid limestone of Weller, 1920	Birdsville group	
			Bed 11	Degonia sandstone of Weller, 1920		
			Bed 10	Clore limestone		
			Bed 9			
			Bed 8			
			Bed 7	Palestine sandstone		
			Bed 6	Menard limestone		
			Bed 5	Tar Spring sandstone		
			Bed 4	Glen Dean		
			Bed 3	Hardinsburg sandstone		
			Bed 2	Golconda formation		
			Bed 1	Cypress sandstone		
	Tribune limestone		Gaspar	{ Paint Creek—Upper Gasper Yankeetown or Sample ss Renault—Lower Gasper	Montesana limestone or group	
						Cypress sandstone
	Sainte Genevieve limestone	Ohara member		Upper Ohara	{ Zone 4 Zone 3 Zone 2 Zone 1	Shetlerville shale
Rosiclare sandstone		Rosiclare sandstone				
Fredonia oolitic limestone		Fredonia limestone				

In view of the fact that this sequence of lithologic units in western Kentucky was worked out and established in an exceedingly faulted area, any fair-minded man should do no less than concede that it merits the approbation due to a successful piece of pioneer work in detailed stratigraphy rather than the severe criticism that it has received at the hands of Professor Weller,³ who in fact required 10 years of work in the less disturbed areas in Illinois before he finally recognized the full sequence of Chester deposits. That I in my 1905 publication was unfortunate in (1) the choice of the name "Tribune" limestone, (2) in applying Engelmann's term Cypress to a lower sandstone than the one to which it actually pertains, and (3) in locally assigning the Ohara zone 4 to the

³ Stuart Weller: The geology of Hardin County. Illinois State Geol. Survey, Bull. 41, 1920; Jour. Geology, vol. 288, nos. 4 and 5, 1920. Geology of the Golconda quadrangle. Kentucky Geol. Survey, 1922.

lower part of the Bethel ("Cypress") sandstone, is frankly admitted in a more recent publication on the subject.⁴ I admitted also various errors in correlating the Kentucky formations with beds found in the Mississippi Valley. Though most of these errors of fact and judgment did not originate with me, but were inherited from predecessors in the field, I nevertheless accepted full responsibility for them. But, after all the necessary nomenclatural substitutions had been made and new formational names had been given to the beds which I had designated by numbers merely, the sequence of formations and beds remained in practically all essential respects precisely as I gave it in 1905.

However great the confidence of others in my judgment may be, their confidence must be shaken when the data on which my conclusions were grounded are denied or questioned. Therefore it is not only a right, but also an obligation, that I owe to the science to defend the assailed facts and inferred correlations and to support them with such new observations as field and laboratory investigations in the meantime have granted.

PUBLICATIONS ON CHESTER FORMATIONS IN PAST DECADE

Since 1905 various publications devoted in large or small part to Chester problems have appeared—three prior to January, 1922, and one since by Prof. Stuart Weller,⁵ one by Mr. Charles Butts,⁶ and one by myself.⁷ In the last, as already mentioned, all the errors of observations and interpretation that subsequent investigations had revealed in my 1905 publication were conceded and corrected. In the meantime, also, Mr. Butts and I had come into close agreement on all but two points, namely: (1) he preferred to propose a new name—Bethel sandstone—for the formation that I had described and mapped in 1905 under the name Cypress sandstone, whereas I advocated the use of Keyes' name, Aux Vases sandstone, instead; (2) he believed, and therein agreed with Weller, that the upper beds of the Sainte Genevieve limestone pinch out, in going eastwardly and southwardly from Caldwell County, until only the Fredonia member of the formation remained, whereas I held that the upper beds merely lost their shaly character and passed laterally into thinner, mainly oolitic limestones. Mr. Butts now accepts the latter interpretation.

One of the two papers published by Weller in 1920 appeared in the

⁴ Mississippian formations of western Kentucky. Kentucky Geol. Survey, 1917.

⁵ Trans. Illinois Acad. Sci., vol. 6, 1913, pp. 118-129; Illinois State Geol. Survey Monograph 1, 1914, pp. 23-29; Illinois State Geol. Survey, Geology of Hardin County, 1920. Geology of the Golconda quadrangle. Kentucky Geol. Survey, 1922.

⁶ Kentucky Geol. Survey, Mississippian series in western Kentucky, pt. 1, 1917, pp. 46-119.

⁷ Kentucky Geol. Survey, Mississippian series in western Kentucky, pt. 2, 1917, pp. 1-272.

Journal of Geology under the title "The Chester series in Illinois." Aside from matter that is repeated in all of his later publications on Chester formations—he never forgets to expose the mistakes of Ulrich—this paper is notable because of a new classification of the Mississippian system, differing from all preceding by the division of the Chester into three groups and the system into but two series, the Chester series above and the Iowa series below. The boundary between the two is drawn at the base of the Aux Vases sandstone. Regarding these innovations, it is hardly necessary to say that I can not accept them. My objection to drawing a major boundary between the Sainte Genevieve and the Aux Vases has in the course of years only grown more firmly rooted; and I see as many reasons as ever for an important line between the Warsaw and the Keokuk. Then, as regards the asserted taxonomic equivalence of the "Iowa series" and the "Chester series," even excluding the Sainte Genevieve group, it seems to me that Weller has unduly emphasized the Chester and greatly underestimated the importance of the Meramecian, Osagian, and Kinderhookian epochs. About half of the Chester units that he recognizes as distinct and full-pledged formations should be merely lithologic members of broader units that might with propriety be called formations. The sandstones in most or all of the Chester instances are but clastic introductions of the succeeding limy stages. They are useful datum planes in classifying a most variable series of deposits, and so I am glad to distinguish them by the names assigned to them by Engelmann, Keyes, Butts, and Weller. But outside of Illinois, Indiana, and western Kentucky, the Chester sandstones may be entirely wanting without materially reducing the completeness of the sedimentary record.

MATTERS IN CONTROVERSY WITH PROFESSOR WELLER

The more important matters on which Weller held and still holds views differing from mine were vigorously defended in the volume published for me by the Kentucky Geological Survey in 1917. These disagreements pertained (1) to the basal boundary of the Chester group, I having included the whole of the Sainte Genevieve limestone in the Chester, whereas Weller draws the line at the top of what I have, for purposes of discussion, designated as the "Lower Ohara" or zone 1 of the Ohara member of the Sainte Genevieve.

(2) I correlated the sandstone to which I wrongly applied the name Cypress in 1905 with the Aux Vases sandstone of the Mississippi Valley, whereas Weller now adopts the name Bethel for this sandstone and correlates it with his Yankeetown formation, which is typically developed in Monroe and Randolph counties, in western Illinois. The Aux Vases

sandstone is regarded by Weller as wanting in Hardin County, Illinois, and in Kentucky, where its position is said to be indicated by a supposed unconformity between my Ohara zones 1 and 2. I, on the contrary, have denied this reputed absence of the Aux Vases sandstone and have attached little importance to the local break between Ohara zones 1 and 2.

(3) I recognize a representation of the Upper Ohara (zones 2, 3, and perhaps 4) in the vicinity of Sainte Genevieve, Missouri, and in Union County, Illinois. In the former place this representative underlies the typical Aux Vases sandstone and in the latter place it underlies beds of sandstone and shale that I regard as corresponding to the Aux Vases. Weller, on the contrary, denies the presence of the Upper Ohara in the first of these places beneath the Aux Vases, and prior to 1920 regarded all of the Upper Ohara as corresponding to his Renault formation, which, like the Yankeetown formation, is typically developed in the Mississippi Valley proper and there overlies the Aux Vases sandstone. In his Hardin County Report, however, he places only the cherty top zone 4 of the Ohara on the plane of the Renault, zones 2 and 3 now being distinguished as a distinct formation, named Shetlerville limestone, concerning which he is uncertain whether it corresponds to the Aux Vases sandstone or belongs in a hiatus between that sandstone and the overlying Renault.

(4) I am inclined to contemporize the lower half of the lower two-thirds of the Okaw limestone of Randolph County, Illinois, with the Cypress sandstone of southern Illinois and western Kentucky; also, to regard the Golconda shale and the limestone as unrepresented in the Randolph County section. Weller, on the other hand, correlates the Golconda with the greater lower part of the Okaw and the Cypress as passing laterally into a thinner sandstone in Randolph County, to which he applied the name Ruma sandstone.

Regarding the fourth of our major differences I shall say little on this occasion beyond the bare statement that I still regard the Middle, and perhaps also the Lower, Okaw as distinct from the Golconda. The evidence in this case is mainly negative: the most characteristic of the Golconda fossils have not been found in the Okaw limestone, and those of the Okaw have not been observed in the Golconda. The half dozen or more of small mollusks that are common to the two formations are of types that range with so little modification from the Spergen on to the Pottsville that I am little inclined to credit their testimony with much value in refined stratigraphic correlations. It is precisely these small pelecypods and gastropods in the Okaw limestone that in 1905 misled me into correlating this limestone with the Gasper limestone of Kentucky, in which very similar, if not precisely the same, species are found.

The reasons for my opinion concerning the relations of the Cypress sandstone to the Okaw limestone were discussed at considerable length in my 1917 publication on the formations of the Chester series, but the facts in this case are not sufficiently convincing in either direction to warrant a quarrel with Professor Weller in seeking a solution of the problem. Our respective views on the subject may stand as they are until more definite evidence is discovered.

Regarding the first, second, and third disagreements, I devoted about 150 pages of the book on the Mississippian series in western Kentucky to the description and mention of the facts as I saw them in the several cases. Then, after adding 60 pages of argument, it seemed to me I had covered the ground so thoroughly and answered the many questions so well that a successful refutation of my views, or even reasonable doubt regarding the validity of my position, would be impossible. That this confidence was not warranted in the case of a determined opponent like Professor Weller is clearly shown by his unyielding attitude in subsequent publications.

THE REPORT ON HARDIN COUNTY, ILLINOIS

Weller's most important publication on the Chester appeared toward the close of 1920.⁸ It is included in an excellent presentation of the stratigraphy of Hardin County, Illinois, partly in collaboration with Charles Butts, but fails to command the respect and appreciation that I would like to give it because of the numerous instances of unfair and often unnecessary criticism that he accords to my observations and opinions. Mere contradiction, whether by definite words or implication, can avail but little toward arriving at the truth. Nothing less than indisputable logic and facts serve the purpose.

In the Hardin County report Professor Weller attacks not only many of my conclusions and opinions, but also the methods and principles employed in reaching them. Particularly among the latter is the principle of determining geologic contemporaneity by precise matching of structural or character combinations involving not only the generic and broader specific characters of the fossils, but more particularly the biologically less important features by which we distinguish varieties and minor mutations. I hold, namely, that any combination of twenty or more characters—and it would be a very simple thing indeed that has

⁸ Since this paper was written and read at the Amherst meeting another report dealing with Chester formations in western Kentucky, part of the Golconda quadrangle, has been published for Professor Weller by the Kentucky Geological Survey. Many of the criticisms of Ulrich's work previously discussed by him in the Hardin County report are repeated and in instances amplified in this later work.

fewer characters—can not have been evolved either before or after the particular time in geologic history in which it existed. In other words, no such combination of major and minor features can have occurred more than once; hence I maintain that the occurrence in two or more places of accurately identified specimens of species or varieties that are alike in all details of structure affords the most reliable known means of establishing the contemporaneity of the beds from which the fossils were taken.

Of course, like any other means of correlating geologic formations, this principle must be applied with discretion and all due regard to differences marking stages of growth and to those that are to be counted as strictly individual.

Weller treats me ungenerously and with actual unfairness in his discussion and frequent reiteration of the fact that in 1905 I applied the name Cypress to a sandstone formation that is older than the one at the type locality of the Cypress. Nobody then knew—nor did any one, including Professor Weller, suspect before 1915, when Butts, after joining Weller in the study and areal mapping of the formations in southeastern Illinois, discovered the facts in the case—that the true Cypress on reaching the Ohio at Golconda dropped in the section almost into contact with another older sandstone, the two together making the bluff along the river through most of the distance between Golconda and the Hardin County line. Neither did Weller nor any other geologist know before Butts' discovery of the tripartite character of the sandstone bluff that the sandstone in Downeys Bluff at Rosiclare, which had been mapped by Worthen and Engelmann as the Cypress sandstone and which was my type of the sandstone that I mapped under this name in Kentucky, is in fact only the lower of the two sandstones occurring in the bluffs both above and below the town of Golconda.

The misnaming of the Tribune limestone and my erroneous correlation of this limestone with the subsequently named Okaw limestone of the section in western Illinois was admitted and explained in the Kentucky Survey volume. Besides, the name Tribune has been dropped and the Gasper limestone, by which name the formation described by me in 1905 under the discarded term is now generally known and accepted, is fully described and clearly defined by both Butts and myself in the Kentucky work. Surely this kind of "rubbing it in," including a quotation (page 128) from a letter written by me in 1911, can serve no good purpose. It would have been more generous and better all around to have ignored and forgotten such relatively trivial lapses. The only thing worth remembering about the Tribune limestone is that under this name

I described a definite lithologic and stratigraphic unit of the Chester series, which has since been recognized by the characters then ascribed to it, from Caldwell County through southern and eastern Kentucky into southwestern Virginia and Tennessee and thence into Alabama. That I failed to select a satisfactory name for this limestone, which would have secured for me the credit of naming so important a formation, might be counted as more of a misfortune than a misdemeanor.

But, while these and other instances of ungenerous treatment might safely be left to the judgment of fair-minded readers, there are other statements in Weller's Hardin County Report that may not be passed by with like confidence in the outcome. Much of the paleontologic and stratigraphic evidence published by me he ignores entirely, and some of this is very clearly out of harmony with his own statements and conclusions.

In other places he states my conclusion on the question under discussion and dismisses it with the simple, unqualified, and wholly unsupported assertion that there is no reason or basis "whatsoever" for it. And yet in each of the two or three cases of this kind I gave the evidence on which the opinion is based and devoted two or more pages to its discussion. Whether my evidence in these cases appears weak or strong in the opinion of others, it certainly deserves more respectful treatment than Weller gives it.

And then there are matters of fact—indeed, very many of them—such as the occurrence and range of fossil species or the identification of particular zones or formations. When my account of them disagrees with his own experience or belief, he either ignores it completely or seeks to discredit it in one way or another. In cases where he has chosen the latter course he implies either incompetence, carelessness, or insincerity on my part; and in more than one instance, to make good on his refutation, he cites only those parts of my statement that fit in with the point he seeks to make.

THE LOCALITY NEAR LEVIAS, KENTUCKY

To give an example of implied incompetence and incomplete statement of fact, I refer to what he says, first on page 130 and again in nearly the same words on page 141, about

"the one locality that has always been mentioned by Ulrich in discussion of this question [the occurrence of *Fredonia* fossils in the Upper Ohara], where he claims to have collected *Platycrinus penicillus* and other unquestioned Sainte Genevieve species in the 'Upper Ohara,' is near Levias, in Crittenden County, Kentucky, where the fossils are said to have been secured less than 50 feet beneath the sandstone formerly called Cypress by him, but now

renamed Bethel by Butts. A visit to this locality in the summer of 1918 by the writer in company with Mr. Charles Butts established the fact that the Rosiclare sandstone had been mistakenly identified and mapped as Cypress by Ulrich, and that consequently these Sainte Genevieve limestone species were actually collected from the Fredonia limestone instead of from the 'Upper Ohara.' "

Now there are two features about this quoted statement by Weller that need attention. In the first place, I have always mentioned, in speaking of this fauna found by me near Levias and also published on page 157 of the Kentucky Report, that the *Platycrinus* occurred at this place in the same layer of shaly rock with several species, among them the coral *Amplexus geniculatus*, that are known to occur only in the Upper Ohara or in higher positions. Regarding this coral, Weller thinks so well of it as a guide fossil that he uses its name in giving a faunal designation to the Ohara zone in which it is commonly found. But why, I may justly ask, does he omit all mention of *Amplexus geniculatus* in this and other attempts to discredit my statements as to the local presence in the Upper Ohara of western Kentucky of *Platycrinus penicillus* or *huntsvillæ*, as it was called by Wachsmuth and Springer and myself? And why, again, does he ignore the statement made by me at the same time that I collected this *Platycrinus* "above the conglomeratic bed at Cedar Hill, near Princeton"—the type locality of the Ohara—where he knows very well there is no possible chance of confusing the Rosiclare and Bethel sandstones? Let us consider all of the evidence and not only that part which is regarded as favoring particular views.

The second feature concerns the asserted establishment of the fact that I had mistaken the Rosiclare sandstone for the Bethel. That I should have done so seemed to me not only highly improbable, but almost impossible. The two beds, as a rule, are so very unlike. To make sure of this, Mr. Butts and I visited the locality near Levias in June, 1921. A mineralized fracture with small displacement of beds runs lengthwise through the valley. The downthrow is on the east side of the vein. On the west side, which I had not previously visited, the area having been mapped by an assistant, we found and immediately recognized the Rosiclare sandstone and under it the Fredonia, with its usual characteristics. But this was not the place where I had found the fossils. After a brief search I recognized the spot on the east side of the vein, in the slope of the hill that is capped by the Bethel sandstone to a near-by larger fault. Approximately 50 feet beneath the Bethel and fully 30 feet above the Rosiclare we found the shaly bed from which the fossils in question were collected in 1903, on the occasion of a very hurried visit to a prospect a

hundred yards or so to the west of the fossiliferous outcrop. Beneath the shaly bed we found the Ohara zone 1 and under it the same unmistakably characteristic Rosiclare sandstone as on the west side of the vein.

In this manner, then, Professor Weller's statement regarding my mistakes at the Levias locality is completely negatived.⁹ To place beyond all reasonable doubt this matter of the occurrence of fossil species that Weller mistakenly insists do not occur in the same formation, but which I have found together not only here, but at a number of widely separated localities, to be reported on later, I shall give the list of 30 species collected in 1903 from the bed in question. The x preceding 11 of the names signifies that the species so marked is also on a small slab 6 inches long, 3 inches wide, and half an inch thick that was collected at or near the original spot in 1921.

List of Fossils from shaly Bed 30 to 35 Feet above the Rosiclare Sandstone and about 50 Feet beneath the Bethel Sandstone, about one-half Mile southeast of Levias, Kentucky, on east side of Miller Mine

<i>Triplophyllum spinulosum</i>	<i>Fenestella elevatipora</i>
<i>Amplexus geniculatus</i>	x <i>F. serratula</i>
<i>Dizygocrinus</i> cf. <i>superstes</i>	x <i>F. tenax</i>
x <i>Platycrinus</i> cf. <i>penicillus</i>	x <i>F. n. sp. (same in Missouri)</i>
x <i>Pachylocrinus</i> cf. <i>scoparius</i>	x <i>Polypora spinulifera</i>
<i>Taxocrinus</i> cf. <i>huntsville</i>	x <i>P. cf. approximata</i>
<i>Pentremites pulchellus</i>	<i>Rhombopora</i> cf. <i>tabulata</i>
<i>P. cf. buttsi</i>	x <i>Cystodictya labiosa</i>
<i>Fistulipora</i> cf. <i>excellens</i>	<i>Glyptopora punctipora</i>
<i>F. sp. 2</i>	<i>Orthotheses kaskaskiensis?</i>
<i>Eridopora</i> cf. <i>punctipora</i>	x <i>Diaphragmus montesana</i>
<i>E. sp. 2</i>	<i>Spiriferina transversa</i>
<i>Stenopora tuberculata</i>	x <i>S. subspinosa</i>
<i>Lioclema?</i> <i>araneum</i>	<i>Cliothyridina sublamellosa</i>
<i>L. aff. araneum</i>	<i>Pugnoides ottumwa</i>
x <i>Fenestella cestriensis</i>	<i>Phillipsia</i> sp.

Except the first two of the crinoids and the *Pugnoides ottumwa*, which are common Fredonia species that Weller claims he has never found

⁹ Mr. Butts has kindly volunteered the following signed statement: "I am glad to substantiate Mr. Ulrich's published statement regarding the horizon from which he obtained slabs bearing *Platycrinus penicillus* together with *Amplexus geniculatus* and other fossils usually regarded as characteristic of the Shetlerville beds of the Upper Ohara. A thin layer of shaly limestone of the same character as the specimens referred to by Mr. Ulrich occurs at the place described by him, about 30 feet above the Rosiclare sandstone. Though no *Amplexus* was found in the small exposure, *Platycrinus penicillus*, associated with other species usually found in the Shetlerville formation with that coral, was found, and there is no reason to doubt that this layer is the source of the fossiliferous slabs found many years ago by Mr. Ulrich in this immediate vicinity and reported on by him in 1917.—CHARLES BUTTS."

above the "Lower Ohara," the above list is an eminently characteristic Shetlerville association.

COMPARISONS AS TO RELATIVE ABUNDANCE AND QUALITY OF EVIDENCE

Instances where Weller makes it appear that he has thoroughly investigated and considered all the evidence extant, whereas my Kentucky report contains evidence that opposes his conclusions and which he either overlooked or thought it best to ignore as untrustworthy, are numerous. For most of the Chester formations that he describes in the report on Hardin County the lists of fossils published by me in 1917 comprise more species than he cites. Thus my list of *Fredonia* fossils¹⁰ mentions 151 species from localities in western Kentucky. His list from the same limestone in Hardin County mentions only 54 species. Of my list of 151 species of *Fredonia* fossils 50 are marked as ranging into the Upper Ohara and 56 as represented by close or undistinguished descendants in the higher Gasper limestone. These upward-ranging *Fredonia* species are almost entirely ignored by Weller, and regarding the few that he takes into consideration at all he implies that, as he himself has not found them in the *Fredonia*, I must be mistaken either in the identification of the fossils themselves or in the age determination of the beds in which they were found; or if neither of these possibilities apply, then I must have carelessly mixed the fossils from different zones and formations. That any of these three conditions may have obtained in rare instances I will admit frankly enough; but that I was ever either careless in locating my fossil collections or often in error in recognizing particular stratigraphic zones I can not concede, nor do I believe that many geologists would accuse me of such shortcomings. Why, it is on the quality of precision in the location of fossil zones and in their recognition from place to place that whatever of pride I have had in my work in geology mainly rests.

My 1917 list of the fossils found by me in the Upper Ohara also exceeds considerably the number of species credited to the same beds by Weller. This list does not include all of the species in my collections from these beds, but it comprises 93 of them, of which not more than 5, two of even these being doubtfully identified in lower zones, are cited as confined to zone 4, which Weller now refers to the Renault formation. This leaves 88 against 72 named in Weller's list of the fossils recognized by him in his Shetlerville formation, which corresponds to my Ohara zones 2 and 3. The 16 or more species in my list that are not given in Weller's are all included among the 54 Upper Ohara species that I have

¹⁰ Op. cit., pp. 133 to 137.

recognized also in the underlying Fredonia limestone. Most of the remaining 38 of these 54 species that I have designated as common to the Fredonia and the Upper Ohara are among the species that Weller found and listed in the Shetlerville fauna but not in the Fredonia.

Evidently I have been either more fortunate or more industrious in my collecting of Sainte Genevieve and Gasper faunas. Whatever the reason, Weller has no right to ignore the faunal part of the evidence on which I based my conclusion that the Fredonia member of the Sainte Genevieve is more closely allied to the Chester than to the underlying Saint Louis and Spergen formations of the Meramec group. In the face of the opposing evidence cited by one who has collected or determined more fossils from the concerned formations than Weller has, he most certainly is not warranted in declaring, definitely and without qualification of any kind, that "not a single member of the [Lower Ohara; hence inferentially also the preceding Fredonia] fauna is a distinctive Chester type"—a sentence quoted from page 120 of his report on Hardin County. Indeed, his own list of Shetlerville fossils on page 140 contradicts this statement by showing that of 17 Shetlerville species that he recognizes also in both the Renault and the Fredonia 6 have no known near relatives in pre-Sainte Genevieve beds, 6 others are represented by close, though distinguishable, relatives in the older formations, and 5 range from below to above the Sainte Genevieve. The first 6 of these Fredonia species therefore fulfill all the requirements of distinctive Chester types.

Moreover, if Weller had compared his small Lower Ohara collection (15 species) with fossils found in the Gasper limestone in Kentucky, as listed by me in 1917,¹¹ he would have observed that at least 10 or 11 of the 15 species occur also in that unquestioned Chester limestone. Of the remaining 4 species the *Platycrinus* positively does range upward at least into the Upper Ohara, whereas the *Cypricardinia* is of a type that might be found in any Upper Mississippian oolite, and the two species of *Aclisina* have no established stratigraphic significance. As might be expected, all of these Lower Ohara species except, perhaps, the *Aclisinas* occur also in the Fredonia and most of them begin in the Spergen. However strictly compared and evaluated, the predominance of the affiliations of this Lower Ohara faunule is Chesterian rather than Meramecian. Obviously, too, it is but a very incomplete sample of the marine life of its time.

CHESTER TYPES IN THE FREDONIA FAUNA

A much better conception of the marine fauna of the pre-Upper Ohara part of the Sainte Genevieve formation is to be obtained from my list of

¹¹ *Op. cit.*, pp. 149-152.

Fredonia species.¹² This comprises more than 150 species and includes many species that are well entitled to be designated as distinctive Chester types. Indeed, my analysis of the Fredonia fauna indicates that 70 per cent of the total Fredonia fauna as known to me is more closely related to subsequent Chester fossils than to preceding faunas.

Running through my published long list of Fredonia fossils, I have selected the following as clearly meriting, in the present state of our knowledge, the distinction of being considered as Chester rather than Meramec species: *Triplophyllum spinulosum*, *Michelinia* n. sp., the four species of *Pentremites*, *Anisotrypa fistulosa*, *Rhombopora persimilis*, *Cystodictya labiosa*, *Fenestella* cf. *cestriensis*, *F. elevatipora*, two species of *Polypora*, *Archimedes meekanus*, *Thamniscus furcillatus*, all four of the species of *Productus*, *Diaphragmus montesana*, *Spirifer* cf. *leidyi*, *S. pellensis*, *Reticularia setigera*, three of the species of *Spiriferina*, the four species of *Aviculopecten*, at least 12 of the remaining 21 pelecypods, and 14 or 15 of the 37 gastropods, 7 of the remaining 22 gastropods being as near Spergen species as to Gasper forms, while the others are of unknown stratigraphic significance. Evidently the trend of the fossil evidence is, like that afforded by comprehensive and geographically extended study of the physical criteria, much more decisively favorable to the inclusion of the Sainte Genevieve in the Chester series than Weller would have us believe.

THE UPPER OHARA FAUNA

In discussing my list of Upper Ohara fossils Weller¹³ goes beyond the bounds of fairness and prudence. I quote him as follows:

"The fauna of the Shetlerville horizon is that of the so-called zone 3 of the Ohara limestone as recorded by Ulrich, and the faunal evidence as presented by him exhibits an association of the characteristic Sainte Genevieve species, *Platycrinus penicillus*, with the *Amplexus geniculatus* and its associates. This supposed association is one of the strongest evidences Ulrich has presented for his union of the 'Upper Ohara' with the Sainte Genevieve, and consequently his inclusion of the Sainte Genevieve in the Chester group. The published list of this fauna, however, as presented by Ulrich, is grossly misleading as to facts. He has not separated his faunal lists in accordance with the localities from which they were collected, but has lumped together in one composite list all those forms from all of the collections which he has either correctly or incorrectly considered as representing this horizon."

In the first place, he should have said that his Shetlerville formation embraced not only my zone 3, but also zone 2, both being above the con-

¹² Op. cit., pp. 133-137.

¹³ Hardin County Report, p. 141.

glomerate in the Cedar Hill section, which he says marks the base of his new formation. Next, it is not quite true that I failed to separate the Upper Ohara faunal lists according to localities, but in grossly misleading manner lumped together in one composite list all those forms from all of the collections which I either correctly or incorrectly considered as representing the horizon of the Shetlerville. Regarding the latter matter the facts are as follows: In my Kentucky report, on page 138, which immediately precedes the list complained of, I state that practically all of the positively located material from zone 2, which includes specimens of two forms of *Platycrinus huntsvillæ*, was collected by me at Cedar Hill, near Princeton, the type locality of the Ohara and probably the best and most complete exposure of its beds known. Then I proceed to say that as the overlying zone 3 at Cedar Hill is not so profusely fossiliferous as in Crittenden County, the list of its fossils was compiled chiefly from collections made at localities to the west and north of Marion, Kentucky. One of these is the Moore Glade, 4 miles west; the other a very similar glade on the Hard farm, 3 miles north of Marion. These are the only places in Crittenden County where I made any real effort to collect the fauna of zone 3. Besides, the collections from these two localities were the only ones made in this county that were fully determined and listed. Finally, there is absolutely no question as to the strict equivalence of the beds at the two places from which the fossils were taken. Both were fresh and much better collecting grounds when I visited them than they are now, which may account for the fact that I procured more species at the Moore Glade than did Professor Weller, who also reported on the fauna at this place. He lists 40 species, I more than 70.

There was, therefore, no more reason to doubt that the Upper Ohara fossils listed by me actually came from the zones to which I credited them than there would be for me to question that the fossils determined by Weller, whether correctly or incorrectly, and listed by him as occurring in a given bed at some particular locality, actually came from the bed and place to which he credits them. To express doubt in either case is little short of questioning an author's integrity; and, if not that, then it amounts at least to casting doubt on his capabilities as a stratigraphical geologist.

·
*OCCURRENCES OF PLATYCRINUS, DIZYGOCRINUS, AND PUGNOIDES IN THE
UPPER OHARA*

These unwarranted statements by Weller evidently are inspired by his desire to weaken or eliminate evidence that is clearly fatal to views concerning the stratigraphic and faunal relations of the Fredonia oolite to

the Upper Ohara and Gasper limestones, and therefore to the Chester group, which are held by him in opposition to those previously published by me. His views on these questions can not be successfully maintained if such fossils as *Platycrinus huntsvillæ*, *Dizygocrinus superstes*, and *Pugnoides ottumwa*, which he regards as entirely confined to and characteristic of the Sainte Genevieve beds beneath the Upper Ohara, actually do range upward into the Upper Ohara, as claimed by me. But I have known for more than 30 years that these three fossils are not strictly confined to pre-Upper Ohara zones in western Kentucky, where I found them well up in the Ohara at three places—in Caldwell, Crittenden, and Livingston counties. Moreover, I can now add that the two crinoids, together with *Globocrinus*, are exceedingly abundant, though very locally distributed, in the vicinity of Huntsville, Alabama, in beds now definitely correlated with the Upper Ohara.

But we know of other occurrences of this Upper Ohara crinoid fauna which may be recognized even when the *Platycrinus* is lacking, as happens locally in southeastern Kentucky. Among the most important of these occurrences is one in Owen County, Indiana, where an excellent but very local development of this fauna, including *Platycrinus penicillus*, was found. It occurs also in Monroe County, Illinois, near Burksville, in a shaly bed that was and may yet be referred by Weller to his Renault formation. I shall have more to say of these occurrences and also give lists of fossils on following pages.

Regarding the presence of both *Platycrinus penicillus* and *Pugnoides ottumwa* in beds regarded by me as corresponding to some part of the Upper Ohara or possibly to an even younger horizon than the Shetlerville, I shall add here only a few words concerning recent observations in Sainte Genevieve County, Missouri, namely: During the past summer Mr. Butts and I found these two species, together with a pentremite of the type of *P. buttsi*, which is a highly characteristic Upper Ohara fossil, a short distance south of Aux Vases River, in limy shale making the upper 5 feet of the Sainte Genevieve, as delimited by me. This observation was quite in harmony with views previously held as to the components of this formation in Sainte Genevieve County; but the discovery, at the same time and place, of a limestone and shale horizon within the Aux Vases sandstone, out of which we procured a fauna of 41 species, among which again are bases and columnals of *Platycrinus huntsvillæ* and typical *Pugnoides ottumwa*, was altogether unexpected. In fact, it was distinctly shocking to my idea of the proprieties to find that these excellent and elsewhere steadfast Sainte Genevieve guide fossils had here apparently transgressed their allotted ranges. But what can the dis-

tressed paleontologist do under such all too frequent happenings except submit and adjust himself to the inevitable facts?

FIELD INVESTIGATIONS IN 1921

REVIEW OF ITINERARY

In view of preceding statements, it must be clear that Weller's unyielding attitude made further field-work and closer study of both the old and the new data essential before we could hope to settle the questions at issue. Responding to this conviction, I entered the field in May, 1921, accompanied by Mr. Butts, hoping to find what we needed. None of the



FIGURE 1.—Sketch Map showing Localities studied

Chester localities visited was entirely new to either of us. The first was at Big Stone Gap, in southwestern Virginia, where we studied an excellent display of the typical Montesana facies of the Lower Chester. Although the section is clearly exposed in a large quarry, we found it impossible to draw a sharp or otherwise satisfactory boundary between the Sainte Genevieve and Gasper parts.

Next we entered the region about Huntsville, Alabama, where we succeeded in clearing several doubtful points. From Huntsville we went to

the area in southern Kentucky between Somerset and Cumberland River, where also we succeeded in finding much of what we hoped to see.

From here we went to Crittenden County, in western Kentucky, where I desired to see again the locality near Levias at which Weller and Butts had claimed that I had made the almost unpardonable error of mistaking the Rosiclare sandstone for the Bethel. But, as I have already shown, this visit proved that, in this case at least, the facts are essentially as I reported them in 1917.

From Levias then we traveled by auto to Golconda, on the Illinois side of the Ohio, and from there to Anna, in Union County. There we most fortunately met Messrs. Kray and Boos, of the Illinois State Survey, who were engaged in mapping the Dongola quadrangle. They were both full of desirable information and anxious to acquire any we might be able to give them; so we spent three very busy and profitable days in this area.

Finally, we went to Sainte Genevieve County, in Missouri, where again we saw some things that looked a little different on this occasion and others that we had overlooked entirely before.

Mentally reviewing the general results of the past season's work at these widely separated localities, I feel warranted in saying that we found nothing requiring any great change of views previously published by me. I now hold essentially, if not precisely, the same views concerning the relations of the Sainte Genevieve limestone to the Chester that I held in 1905 and reiterated in greater detail in 1917. The only change is by addition of much new evidence from localities in eastern Kentucky and Alabama, all of which is favorable to these views. But the mentioned discoveries in Missouri and further information acquired during the past season in Union and Johnson counties, in Illinois, inject some uncertainty into previously advocated correlations of the Aux Vases and Bethel sandstones and regarding the relations of other thinner beds of sandstone and of beds of limestone and shale that lie above the Aux Vases sandstone in Missouri and also above a sandstone in Union County, on the Illinois side of the Mississippi, that I regard as corresponding to the Aux Vases. I am less satisfied now than I was with previously entertained but unpublished beliefs regarding the relations of these Union County beds to formations found in Hardin County to the east and to those across the Ohio in western Kentucky. Professor Weller's views in these cases, as nearly as I can learn from his published reports and other information, also seem to fail in meeting the facts. In short, the information now in hand suggests difficulties and possibilities not contemplated hitherto by either of us. Perhaps in some of our differences the truth lies somewhere between us. However, I shall present the facts as

we found and saw them and let the reader judge for himself as to their significance.

LOWER CHESTER SECTION IN SAINTE GENEVIEVE COUNTY, MISSOURI

General statement.—Starting on the west, we will first consider the section in Sainte Genevieve County, Missouri. It is represented in the first column on the left of the accompanying chart of columnar sections. Here we find the typical exposures of the two formations that are most prominent in the controversy, namely, the Sainte Genevieve limestone and the Aux Vases sandstone. It contains also a representative of the Renault formation, concerning which Professor Weller and I have differed very seriously. The contact between the Sainte Genevieve and the underlying Saint Louis limestone is decidedly unconformable here. Photographs of this unconformity were published by me in 1917. At the same time similar relations between these two formations were described and illustrated as occurring in Sequatchie Valley, in southeastern Tennessee; and in the meantime Mr. Butts' work in eastern Kentucky has brought out the fact that this break is no less clearly indicated, also, on the eastern side of the Cincinnati axis.¹⁴ In short, the contact between these two limestones is unconformable, or disconformable, if one happens to prefer this term, at all places where this part of the stratigraphic sequence has been observed, from Sainte Genevieve County, Missouri, on the west to northeastern Kentucky on the east and northern Alabama on the south. Moreover, throughout this wide extent this break is much more generally and more clearly indicated than is any other in the stratigraphic interval between the base of the Sainte Genevieve and the top of the Gasper limestone, which brings us to the top of the Lower Chester or Montesana limestone group of my classification.

In view of these facts and also because of the practical absence of satisfactory dividing planes in the Montesana limestone in many excellent exposures in the Appalachian region, I may say that my view concerning the most natural and the best indicated boundary between the Meramec and Chester series is as definitely established as it can be done by the physical criteria of the diastrophic method. As I find abundant support for this conclusion among the organic criteria as well, it obviously follows that I can not agree with Weller, who denounces this part of my classification as "the most serious of Ulrich's mistakes."¹⁵

But to return to the section in Sainte Genevieve County, Missouri: The lithologic characters of the Sainte Genevieve limestone vary greatly

¹⁴ Charles Butts: The Mississippi formations in eastern Kentucky. *Kentucky Geol. Survey* (in press).

¹⁵ *Op. cit.*, p. 129.

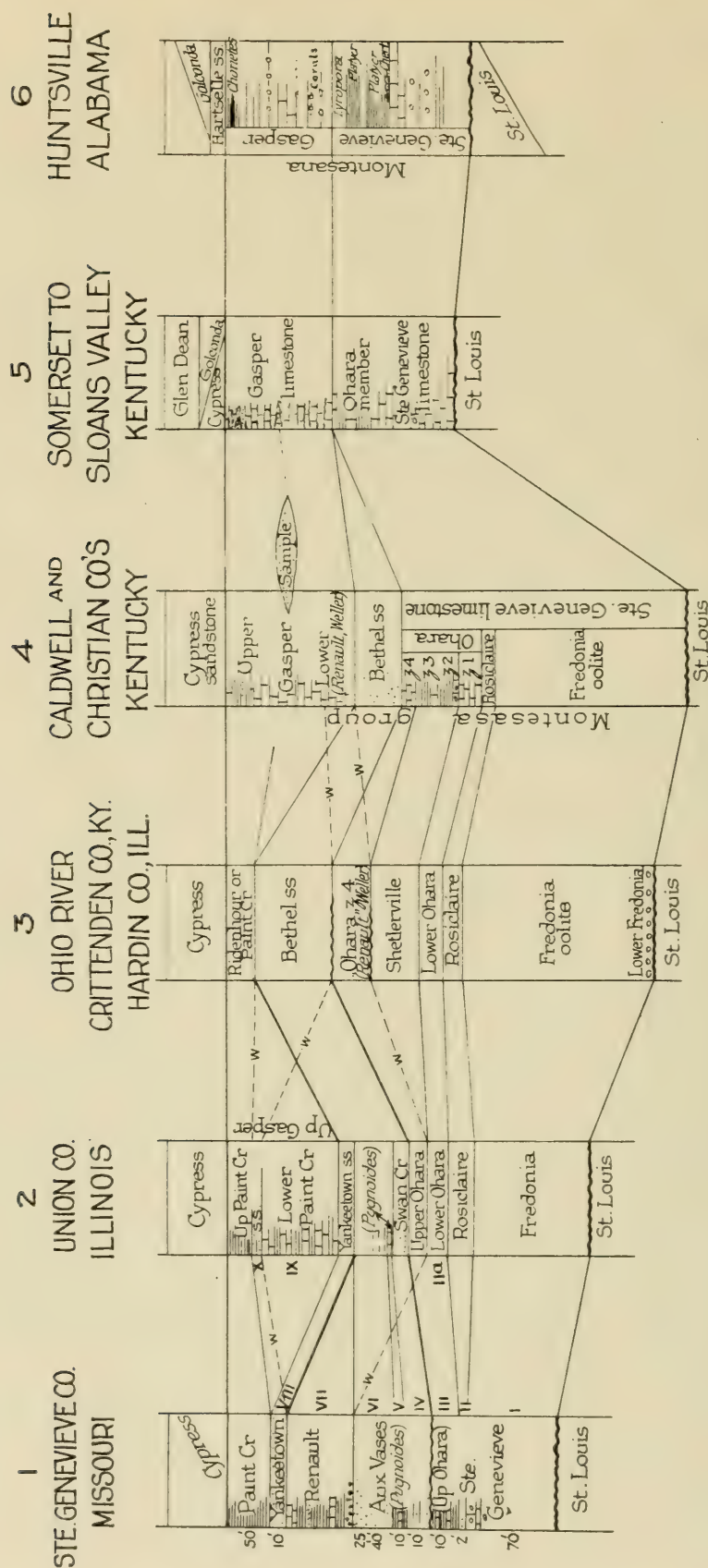


FIGURE 2.—Correlated lower Chester or Montesana Sections

Correlations questioned in heavy lines; Weller's views indicated by broken linesW.....

in tracing the formation along the bluffs from the old Government quarry, 2 miles above Sainte Genevieve, to the south side of Aux Vases River, approximately 5 miles below the town. In the quarry the more or less oolitic lower part of the formation shows extraordinarily well developed cross-bedding for a limestone. This part is succeeded by about 30 feet of yellowish gray, sandy-textured limestone which I regard as including the horizon of the Rosiclare sandstone of the sections in Hardin County, Illinois, and western Kentucky. Over this to the base of the mantle of loess is slightly sandy and shaly limestone with fossils, the most conspicuous of which is a very large and apparently undescribed species of *Bellerophon*, found only at this place.

Going southward from this quarry the cross-bedding of the lower beds, evidently a near-shore facies, changes to horizontal bedding. This prevails in the shallow syncline in which the town of Sainte Genevieve is located. But cross-bedding prevails again in the succeeding low anticline that elevates the unconformable top of the Saint Louis to some 8 or 10 feet above the level of the highway in the bluffs $1\frac{1}{2}$ to $2\frac{1}{2}$ miles south of the town. Here also the sandy character of the higher beds of the Sainte Genevieve is developed in thickness and volume of siliceous content about as in the Government quarry 4 miles to the north. Proceeding from this point to the south side of Aux Vases River, the road crosses another shallow syncline, in the southern half of which the typical exposure of the overlying Aux Vases sandstone occurs in the abandoned Richardson's quarry, out of which the rock used in the construction of the Eads bridge at Saint Louis was procured.

The section shown in the column on the left of the chart was compiled by Mr. Butts and myself from exposures on the two sides of the Aux Vases found along the highway and in near-by places to the east and west. The Cypress sandstone probably does not occur here, and only the lower part of the Paint Creek formation is clearly visible. However, the beds that are most important in this connection, namely, those referred to the Yankeetown, Renault, Aux Vases, and Sainte Genevieve formations, are sufficiently well exposed and characteristic to leave no question as to their character, fossil contents, and stratigraphic relations.

Going downward in this section we may begin with the 10-foot bed of highly siliceous sandy limestone that Weller, Butts, and I are agreed on in correlating with the Yankeetown of Randolph and Monroe counties, in Illinois. Under this is a variable bed of 30 to 35 feet in thickness, consisting mainly of more or less highly fossiliferous limestone, but including layers of shale, sandstone, and conglomerate. Concerning this also we have agreed in calling it Renault. The Renault rests on the Aux

Vases sandstone, the upper member of which consists of 25 to 30 feet or more of massive sandstone. What I am calling the lower member of the Aux Vases consists of 10 to 12 feet of more calcareous and thinner bedded sandstone. Between the two we found, for the first time, last summer a good exposure of calcareous red and green shale and layers of suboolitic limestone, out of which a fauna of 41 species was gotten. These fossils consist mainly of types found in preceding and succeeding occurrences of the well-known Spergen fauna. It is of interest and importance chiefly because it comprises species the vertical ranges of which are in dispute, the most noteworthy of these being *Platycrinus penicillus* or *huntsvillæ* and *Pugnoides ottumwa*. Among the Bryozoa there are two out of three species of Polypora and one of Fenestella that I can only regard as mere varieties of later Chester species which so far have not been observed in any Sainte Genevieve fauna, including, of course, the Upper Ohara beds (zones 2 and 3) that correspond to the Shetlerville formation of Weller.

A marine fauna in the Aux Vases sandstone.—The fossils listed below were obtained from a layer of suboolitic limestone in an 8-foot bed of calcareous red and green marly shale 10 to 18 feet above base of Aux Vases sandstone, exposed in roadside gully between Sainte Genevieve and Saint Marys, Missouri, half a mile south of Aux Vases River.

- | | |
|--|--|
| <i>Platycrinus</i> cf. <i>penicillus</i> (one ring of basal plates and a columnal) | <i>Eumetria verneuillana</i> (large form, with about 50 plications) |
| Two kinds of round columnals of undetermined crinoids | <i>Spirifer leidy</i> (2 forms—one small, the other of medium size) |
| <i>Pentremites</i> sp. (ambulacra only) | <i>Spiriferina subspinosa</i> |
| <i>Stenopora tuberculata</i> | <i>Aviculopecten</i> (4 species, all closely allied to or the same as <i>Fredonia</i> and <i>Gasper</i> species) |
| <i>Fistulipora</i> —2 undet. species | <i>Pteronites</i> sp. |
| <i>Fenestella serratula</i> | <i>Modiola</i> cf. <i>fountainensis</i> |
| <i>Fenestella cestriensis</i> | <i>Sphenotus</i> sp. |
| <i>Fenestella</i> n. sp. (dissepiments thickened at expense of fenestrules, so that the latter are very small) | <i>Parallelodon</i> sp. |
| <i>Polypora cestriensis</i> | <i>Cypricardella</i> sp. |
| <i>Polypora</i> aff. <i>approximata</i> , but with spines | <i>Nucula illinoisensis</i> |
| <i>Polypora</i> n. sp. aff. <i>spinulifera</i> and <i>nodocarinata</i> | <i>Leda</i> sp. |
| <i>Crania chesterensis</i> | <i>Cypricardinia</i> cf. <i>indianensis</i> |
| <i>Orthotetes</i> sp. | <i>Acroculia</i> cf. <i>acutirostris</i> |
| <i>Pugnoides ottumwa</i> | <i>Euphemus</i> aff. <i>randolphensis</i> |
| <i>Pugnoides</i> n. sp. (same in Sainte Genevieve limestone) | <i>Bellerophon</i> aff. <i>sublævis</i> |
| <i>Composita trinuclea</i> (typical form) | <i>Bucanospira</i> aff. <i>textilis</i> |
| <i>Composita trinuclea</i> var. with linguulate production of fold | <i>Orthoceras</i> sp. |
| | <i>Cytherellina</i> cf. <i>glandella</i> |
| | <i>Phillipsia</i> sp. |

I do not know whether Weller has noted this fossiliferous bed between the sandstones as here described. If he has and found the *Platycrinus* and *Pugnoides*, two fossils that he has never believed to range above the base of the Upper Ohara, he would most probably call this marly red and green shale bed Lower Ohara and the sandstone under it Rosiclare. But the latter is not the same calcareous sandstone that two to four miles north of the Aux Vases bridge is regarded as including the Rosiclare and which varies in thickness from 2 to 25 feet in the bluffs to the north and south of Sainte Genevieve. Besides, if the marly bed between the two sandstones were really Lower Ohara, then it would be lithologically very different from any other representative of the Lower Ohara seen by me. It would differ also very decidedly in its fossil contents.

Nearly 20 years ago I observed and noted a section, now unhappily partly covered by building operations, on the south side of the creek at the southern edge of Sainte Genevieve in which the Rosiclare is but two feet thick. Over this came 9 or 10 feet of fossiliferous calcareous red shale and red limestone, and then a 10-foot bed of calcareous sandstone that I believe corresponds to the sandstone of similar thickness and character that I have referred to as the Lower Aux Vases in the section on the south side of the river of the same name. Moreover, in the latter section also there is a hard calcareous sandstone or siliceous limestone that similarly lies about 9 feet beneath the 10 to 12-foot sandstone and which I regard as having the better claim to recognition as Rosiclare.

Under the Lower Aux Vases sandstone, in the section on the south side of Aux Vases River and separating its uneven base from the calcareous sandstone that I take to be the Rosiclare, is a bed, about 9 feet in thickness, made up of red and green sandy shales and two 6-inch ledges of sandy limestone. This bed also contains *Platycrinus* and *Pugnoides*, but the latter includes, besides the typical form of *Pugnoides ottumwa*, another with but a single plication on the fold and none in the sinus. With these occurred part of the cup of *Pentremites* that has a long pyramidal base, and, if we know the form at all, must be the same or near *Pentremites buttsi*. The last has not been found beneath the Upper Ohara in southern Illinois and Kentucky. The other fossils in this bed, as may be seen from the following list, have no special significance, being all of types occurring generally in Sainte Genevieve faunas.

Fauna in top shale of Sainte Genevieve limestone.—The following fauna is from red and limy shale (9 feet thick) at the top of the Sainte Genevieve limestone. The locality is on Sainte Genevieve-Saint Mary's road, half a mile south of Aux Vases River, Missouri.

Platycrinus penicillus—bases and columnals.

Also numerous more or less worn plates and columnals of other crinoids.

Pentremites sp. (A radical plate only, but of such a form that if it belongs to any known Sainte Genevieve or Ohara species it would have to be *P. buttsi*.)

Bryozoa of the genera *Fenestella*, *Polypora*, *Rhombopora*, *Batostomella*, *Stenopora*, etcetera—all too much worn for certain determination.

Pugnoides ottumwa White (especially abundant in top 2 feet). Some of the specimens larger than usual. Two to four plications in sinus.

Pugnoides? sp. nov. Only one high angular plication on fold, none in sinus, and only one or two, the second obscure, plications on either side.

Spirifer leidyi.

Spirifer pellaensis.

Bellerophon—aff. *sublavis*. Apparently same as one in the shaly bed of the Aux Vases sandstone 15 feet above.

No such definitely Upper Ohara fossils as *Talarocrinus dewolfi* and *T. trijugis* are known to occur in these late Sainte Genevieve and early Aux Vases shaly beds in southeastern Missouri. The presence here of such fossils probably would be accepted by all as establishing the age of either or of both of these beds as not older than the Shetlerville stage of the Ohara. At the same time it would leave no doubt as to the truth of my contention that *Pugnoides ottumwa*, as well as *Platycrinus huntsvillæ*, ranges upward beyond the base of the Shetlerville.

Lower Chester section in Union County, Illinois.—Evidence of this nature was found during the past summer in the section near Anna, in Union County, Illinois, approximately 50 miles to the southeast of the Missouri section just described. The Union County section is represented by the second column of the chart. Most of it was observed along Swan Creek, from 1½ to 2½ miles east of Anna. The Fredonia or lower member of the Sainte Genevieve is shown in a large quarry. Over the quarry beds comes first a 10-foot shale bed with lenses of limestone. This is followed by another 10-foot bed of calcareous sandstone that is recognized by all of us as corresponding to the Rosiclare sandstone of Hardin County. The Rosiclare is succeeded first by 12 feet of oolitic limestone, representing the Lower Ohara, and this by 6 to 10 feet of red and green shale with intercalated ledges and lenses of fossiliferous limestone. The first of these limestone ledges is ferruginous and sandy and in other ways suggests an agglomerate. This shaly bed is important because among its fossils we note the presence of bulbous plated calyces of one or more species of *Talarocrinus* like and in part probably the same as *T. trijugis*. Because of the presence of these crinoids, Weller has, and probably does yet, refer this bed to his Renault formation. Certainly he would not place it beneath the zone of the Shetlerville. In my opinion,

it is to be correlated with Zone III of the Missouri section; hence it would be Upper Sainte Genevieve and, compared with sections in the Ohio Valley, it should correspond to some part of the Shetlerville.

Over this *Talarocrinus*-bearing zone is a 20-foot bed of sandstone, to which the field designation Swan Creek sandstone was applied. It is succeeded by at least 4 or 5 feet, perhaps 6 or 8 feet, of shale with two layers of limestone, one of them containing on its upper surface numerous large specimens of *Pugnoides ottumwa*. Some of these specimens are quite typical of the species, but the largest have a somewhat strange appearance because of the increase in number of plications with age. However, a precisely similar form occurs in the upper part of the Sainte Genevieve near Fountain, Illinois, and a specimen from that place is figured and referred to *P. ottumwa* by Weller.¹⁶

The Anna section thus gives us the information that was not found in Missouri and proves that *Pugnoides ottumwa* really does range upward from the Fredonia member of the Sainte Genevieve into beds that all concede to be of Chester age. Incidentally it confirms the doubt expressed by me in 1917,¹⁷ that *P. ottumwa* is confined to the Fredonia.

Proceeding with the Union County section, we find the *Pugnoides* zone followed by 16 feet or more of sandy shale and thin sandstone. The sandstone becomes thicker bedded toward the top of the bed and one or more of the upper layers contain fossils in abundance. Nothing particularly characteristic was observed in this fauna except that the association of a dozen or so of species might occur in almost any part of either the Sainte Genevieve or the Gasper. In other words, it is simply a typical Lower Chester fauna.

This is succeeded by about 10 feet of highly siliceous limestone or calcareous sandstone that closely resembles and certainly has all the essential characters of the bed of similar thickness in the Missouri section that we referred to the Yankeetown sandstone. It is followed by a 60-foot series of thin and rather thick ledges of limestone interbedded with layers of calcareous shale, both kinds of rock often being full of fossils. Locally the top 10 to 20 feet consists largely of red shale. Over it is a thin sandstone, in this region apparently not exceeding 5 feet in thickness, and then about 25 feet of shale and thin layers of limestone, rarely well exposed, that fill the space to the base of the Cypress sandstone.

Difficulties in correlating the Union County section.—Now when we try to correlate these Union County lower Chester beds with sections to the northwest and southeast, some very serious difficulties are encoun-

¹⁶ Stuart Weller: Monograph of Mississippian Brachiopoda. Illinois Geol. Survey, 1914.

¹⁷ Op. cit., p. 157.

tered. Compared with the section in Sainte Genevieve County, Missouri, the only bed between the Rosiclare sandstone below and the base of the Cypress above that I, and also Mr. Butts, recognize with anything like confidence as in both is the Yankeetown sandstone. Unfortunately, as I am informed, Professor Weller does not see the Yankeetown in the 10-foot bed near the middle of the debatable interval, but recognizes the Yankeetown in the 5-foot sandstone lying 25 feet beneath the Cypress and correlates both of these thin beds with the much thicker Bethel sandstone of Hardin County, Illinois, and western Kentucky (see chart of correlated sections, p. 826). In harmony with this correlation of the sandstones he refers all the beds between the 5-foot sandstone above and the 12-foot bed of oolite below to the Renault. On the other hand, I see no Renault at all in the Union County section. The 60 feet of limestone and shale resting on what I think is the Yankeetown seem to me to correlate better with the lower part of the Paint Creek and the often shaly middle part of the Gasper limestone in Kentucky than with the true Renault; and the beds III, IV, V, and VI beneath the Yankeetown, as conceived by me, seem to correspond very well to the three members of the Aux Vases sandstone and the underlying top of the Sainte Genevieve as developed in Missouri. The latter conclusion, which with the first automatically eliminates the Renault from the Union County section, is based very largely on the presence of the shale and limestone with *Pugnoides ottumwa* between two beds of sandstone over typical Sainte Genevieve limestone in both sections. The argument favoring the first of the two opinions, namely, that the 60-foot zone, instead of being of Renault age, really belongs to the Paint Creek formation, is much less simple. It would require pages and pages of most detailed faunal and stratigraphic comparisons, involving not only the facts observed along a direct line running from Sainte Genevieve County in Missouri to south central Kentucky, but also those relating to the Chester formations in Indiana. It would, moreover, include discussions of probabilities in the way of sea-bottom oscillations, discussions of areas supplying clastic materials, and regarding other relatively shallow areas within the sea basins in which deposits of any kind might be less in amount and less continuously laid down than in the deeper parts. Although most of these means of reaching the truth have been more or less thoroughly exploited in the past 4 or 5 months, I have neither the time nor the desire to undertake such discussions on this occasion, particularly because I fear the data in hand are not sufficiently conclusive in their trend to permit of attaining entirely satisfactory results. We require more complete

information regarding the facts that may be found in Johnson and Pope counties, which cover the gently synclinal area between Union and Hardin counties. Formations or parts of formations seem to be present in this intervening area that are wanting in the Mississippi Valley to the west and the Ohio Valley to the east. We know what we have in Kentucky and in the highland rims and in the Appalachian Valley to the south and east of Kentucky and are able to correlate the Chester formations very satisfactorily throughout this great extent; but we do not yet know how to explain all of the difficulties encountered in crossing the southern end of the State of Illinois.

In considering the Union County section I am fairly well satisfied with the correlations of the beds from the Saint Louis to the top of the siliceous limestone that Mr. Butts and I regard as corresponding to the Yankeetown. Only the 60 feet of mainly limestone beds above this siliceous rock offer any serious difficulties. Professor Weller refers these limestones to the age of the Renault; and as the Yankeetown overlies the Renault in their typical exposures, he is obliged to place the Yankeetown zone in some higher position in the section. He does this by correlating the Yankeetown with the 5-foot sandstone which rests on these limestones in Union County. I, on the other hand, see no decisive resemblance between either the faunal or the lithologic characters of this questioned part of the Union County section and those of the Renault as developed in Missouri less than 50 miles to the northwest. This difference between sections in areas so little separated is part of the evidence on which in 1917 I postulated an incompletely separated basin in the Mississippi Valley proper that is distinguished from the remainder of the Illinois Chester basin mainly by the Okaw limestone, which is either wanting elsewhere or represented by very different deposits.

The fauna of Bed IX of the section in Union County, Illinois.—As stated, the questionable 60-foot limestone and shale zone (Bed IX of correlation chart) contains an abundance of well preserved fossils. Pentremites of a few species are very common; also fenestellid and other Bryozoa. However, judging from our collections, both *Lyropora* and *Archimedes* are rare and fewer than one would expect. Then there are three or possibly four species of *Talarocrinus*, none of which seems to be quite like any of the three or four species of the genus found in the Renault of Missouri. Two of the four suggest *T. inflatus*, the type of which came from the Renault in Monroe County, Illinois, and also *T. trijugis*, the type of which is from the Upper Ohara in Hardin County. But I am sure that neither is exactly like either of the described species.

The third is represented by a specimen lacking the tegmen. So far as it goes, it fits Weller's *T. planus*, a Paint Creek species in Randolph County, very well. With these also is a species of *Mesoblastus* that is not exactly like the Upper Ohara form of *M. glaber*, but does agree with the Middle Gasper variety of this species. The *Pentremites* are peculiar in that the assemblage compares very badly with that of the *Pentremites* found in the typical Paint Creek beds in Saint Clair County; but it agrees no better with those found in the Renault as typically developed in the Mississippi Valley or in either the lower or the upper divisions of the Gasper limestone in Kentucky. They do, however, compare much better, both as concerns particular species represented and absence of others, with the *Pentremites* found in two other portions, namely, (1) those in the top limestone of the Ohara in Hardin County, Illinois, and in western Kentucky—that is, the Ohara zone 4 which Weller correlates unreservedly with the Renault; and (2) with those of the shaly middle beds of the Gasper and in the basal part of the upper Gasper limestone in Caldwell and more eastern counties in Kentucky. In fact, there are at least two forms of *Pentremites* in these Union County beds that I can not distinguish from species previously distinguished in studying the fauna of Ohara zone 4. One of these I listed in my 1917 report, but without either figures or description, under the name *Pentremites downeyensis*. The other received the manuscript name *Pentremites sayi*. The latter reminds and may well have been derived out of *P. pulchellus*, a widely distributed and abundant Sainte Genevieve limestone fossil, but attains much greater size and has a lower base. In its further development *P. sayi* probably passed into *P. biconvexus*, which is a characteristic Upper Gasper fossil. But I must add the important fact that I have two specimens of *P. sayi* from Red Bud, Illinois, where they were collected from beds thought to be of Paint Creek age. The Bryozoa are represented by an association of species that is distinctly indicative of the Gasper age and not of the Ohara. The few specimens of *Archimedes* found are of the nature of *A. compactus*, whereas the only species of the genus observed in the Ohara is a close relative of *A. meekanus*.

Among the surprises of the fauna is the presence of a coral that seems indistinguishable from the common Shetlerville species, *Amplexus geniculatus*, in every one of four collections made at places varying from two to ten miles north and east of Anna. This coral seemed a striking incongruity in a fauna that is certainly younger than the Shetlerville zones of the Upper Ohara until I came to study a Middle Gasper faunule collected by Mr. Butts at Russellville, Kentucky, in 1919, in which two

specimens of the same coral were found. With the coral and procured out of the same bed occurs a low-based *Agassizocrinus* and *Pentremites gemmiformis*, both species so far observed only in Paint Creek beds in Randolph and Monroe counties in Illinois and in shaly middle beds of the Gasper in Kentucky; also three other as yet unnamed varieties of *Pentremites*, two of them the same as forms found with the *Amplexus* in Union County, the third a near relative of an Upper Ohara species to which I gave the name *Pentremites ovoides*. Finally, and disregarding the usual association of regular Gasper fossils that make up fully half of the faunal list collected at this spot near Russellville, the collection includes dorsal cups of two species of *Talarocrinus* that agree precisely with specimens found in association with the *Amplexus geniculatus* at four of the localities in Union County. To make the correlation reasonably conclusive, there remains to be added only that at Russellville, according to Mr. Butts' section, the part of the Gasper which overlies the lower Gasper and the shaly beds from which the fauna just discussed was collected is thicker by about 30 feet than in any other section measured in Kentucky.

In this manner and by such apparently incontrovertible faunal and stratigraphic evidence we establish the fact that *Amplexus geniculatus* is not confined to the Upper Ohara, but reappears in at least higher zones in Union County, Illinois, and in a definitely recognized Middle Gasper position in Kentucky.

On the whole, then, the evidence of the fossils collected from these doubtful limestones in Union County favor their reference to the age of the Paint Creek formation and to that of the Middle Gasper quite as much or more than to the age of the Renault. Compared with Upper Ohara faunas, which it should be remembered Weller correlates in part at least with the Renault, this fauna is positively younger.

Regarding the age of the overlying 5-foot sandstone which I am informed is correlated by Weller with the Yankeetown of the Mississippi Valley section and with the Bethel sandstone of Hardin County and western Kentucky, I feel certain only that it does not correspond in position to either the Yankeetown or the Bethel. If Butts and I are right in correlating the Renault with the Lower Gasper, a view apparently shared also by Weller,¹⁸ then this 5-foot sandstone can not be the attenuated Bethel, for that sandstone positively underlies the Lower Gasper in Caldwell and Christian counties, Kentucky. Nor can it pass into the Yankeetown if the 60 feet of limestone and shale beneath it belong, as

¹⁸ Hardin County Report, p. 175.

the preceding discussion of the fauna tends to show, in the lower part of the Paint Creek and the middle part of the Gasper.

Unquestioned Paint Creek beds in the Union County section (Bed XI of chart).—The 25 feet of shaly beds above the 5-foot sandstone evidently are only Upper Paint Creek, providing the Paint Creek actually corresponds, as we all believe, to the middle and upper parts of the Gasper limestone. In Kentucky, and especially in northern Alabama, the upper 10 to 30 feet of the Gasper often are shaly and in places include sandstone. Where this shaly upper member is developed, free fossils are likely to be found in great abundance. Its fauna is characterized by abundance and variety of axes of *Archimedes*, which now strongly suggest *Golconda* species of this genus. It is marked also, and we say particularly, by a species of *Chonetes*, the *C. chesterensis* of Weller. Species of *Pentremites* and of crinoids also are found in this bed, but the former are less abundant and not precisely of the same kinds as those found in the lower half of the formation.

Now it seems to be a fact that in southern Illinois also the genus *Archimedes* is plentifully represented in the shaly limestones that lie between the thin sandstone in question and the base of the overlying Cypress sandstone. Further, these screwlike bryozoan colonies are associated there, as in the vicinity of Huntsville, Alabama, with *Chonetes chesterensis*, a brachiopod shell that is everywhere found in, and in Illinois and western Kentucky apparently confined to, the Paint Creek formation and its correlates. When we add to this the fact that the upper shaly member of the Gasper locally includes one or two thin sandstones in Kentucky and Tennessee, it becomes highly probable that the 5-foot sandstone in the Union County section is to be credited with no greater significance than pertains to the similarly located thin sandstones in the Upper Gasper. In other words, there is a strong basis for the belief that it is merely a thin sandstone within the upper half of the Paint Creek formation. The same sandstone apparently extends from Union County into Johnson County, where, if really the same bed, it is exposed in the lower part of the Cache River bluffs section at Indian Point, 6 miles south of Vienna. However, this lower sandstone at Indian Point, which according to Weller is wanting entirely two miles east of Indian Point, may prove to be the Yankeetown, though hardly, and certainly not, the Bethel if the oolitic and crystalline limestones which there lie beneath it are of Lower Gasper age. The Yankeetown itself is likely to prove a continuation of the Middle Gasper Sample sandstone by extension under younger deposits in a roundabout way from west central Kentucky through Indiana into Illinois.

The section in Hardin County, Illinois, and Crittenden County, Kentucky.—But little needs to be said about the section in Hardin County, Illinois, and Crittenden County, Kentucky. The chart shows that here we have a thick sandstone formation, the Bethel. This is separated from the Cypress sandstone by shaly beds that can be nothing else but Upper Paint Creek. Under the Bethel is a full sequence of Sainte Genevieve deposits, including Ohara zones 2, 3, and 4, which I have hitherto distinguished as the Upper Ohara. The chart indicates by different lines the existing discordant views regarding the relations of the several formations and zones to those found in the sections in Union County, Illinois, and in the Mississippi Valley. Weller's views are indicated by heavy broken lines and those here advocated by continuous lines. Though as yet unwilling to abandon my 1917 view as to the equivalence of the Bethel and the Aux Vases sandstones, I am now less well satisfied with this correlation than I was. Probably both of these sandstones pinch out in the intervening and originally synclinal area comprising Johnson County and adjacent parts of Pope and Union counties. Consequently, and in view of the various and readily conceivable possibilities in the case, I am no longer willing to decide definitely that either the whole or any one or two of the three parts of the Aux Vases sandstone lies within the same stratigraphic zone as that of the Bethel. Under the circumstances, therefore, the propriety of using both names in their respective districts is conceded and the final determination of their relations is left to future investigations.

Regarding the zones of the Ohara, of which 2 and 3 fall under Weller's new term Shetlerville, whereas No. 4 is referred by him to the Renault, I hold essentially, if not precisely, the same views as those published in 1917. No. 4, according to Weller's own belief respecting the equivalence of the Renault and the Lower Gasper, can not represent the Renault, because in Caldwell and Christian counties, Kentucky, the Lower Gasper overlies the Bethel, whereas Ohara zone 4, the same as in Crittenden and Livingston counties and also in Hardin County, Illinois, *underlies* the Bethel.

The section in Caldwell and Christian counties, Kentucky.—The Caldwell and Christian County section also requires very little of explanation and comment. Except the Gasper part of the section, the sequence of beds is in all essential features the same as in Hardin County, Illinois. However, it should be stated here that the Ohara loses its shaly character and changes to solid limestone, in large part oolitic, in passing eastward through and beyond Christian County. More important changes from

conditions found in southern Illinois occur in the interval between the Bethel and Cypress sandstones. In southeastern Caldwell this interval has expanded and is occupied by the Gasper, consisting for its greater part of thick-bedded oolite and subcrystalline limestones aggregating 100 feet or more in thickness.

The lower 30 to 45 feet of this mass, commonly referred to as the Lower Gasper, is full of *Pentremites*, more or less dismembered crinoid remains, simple and loosely composite cup corals, and shells of various kinds. The *Pentremites* are represented by excellent specimens of many species which together form a highly characteristic association. Among the crinoids recognizable calyces of *Talarocrinus* only are commonly found. In fact, this is preeminently the *Talarocrinus* zone, no less than 9 or 10 clearly distinguishable species of this genus being found in this bed in Kentucky. Of other crinoid remains, pieces of large columns sometimes attaining a diameter of three-quarters of an inch or more are always present. These may be counted as characteristic of the bed, as columns of equal size are only rarely found above the shale bed which commonly separates the Lower Gasper from the upper limestone of the formation.¹⁹ The corals, too, are to a considerable degree characteristic. This is true particularly of the largest and most broadly conical of the cups, apparently an undescribed species of *Cyathophyllum*.

This Lower Gasper bed is terminated above by a widely though not generally distributed bed of calcareous marls and shale, with thin, highly fossiliferous layers of limestone. This shale bed often is not recognizable to the south of Kentucky, but on tracing the formation eastward into Breckenridge County it passes into a sandstone member to which Mr. Butts has applied the name Sample sandstone. This sandstone extends thence northward into Indiana, and from there probably turns westward, under cover of later formations, to reappear in southern Illinois as the Yankeetown sandstone. Whether this belief is correct or not, it is positively established that the Sample sandstone has nothing to do with the Bethel sandstone.

The bulk of the fossils in this Middle Gasper shale member consists of Bryozoa, and these mainly of flabellate *Fenestellidæ*; but among the others *Cystodictya labiosa* is perhaps the most abundant. The axes of *Archimedes* are mostly of small types and only rarely if ever very

¹⁹ Such columns have been observed above the Lower Gasper at only a few places in Kentucky. Most notable of these is Russellville, where they were found in the bed before described as containing *Amplexus geniculatus*. It is an interesting confirmation of the conclusion tentatively held in that discussion to note the fact that the same kind of column was collected together with the mentioned coral also in Union County, Illinois.

numerous.²⁰ The *Pentremites* also are of small forms and few in number. *Lyropora* has not been observed.

It is in the oolitic layers of the Upper Gasper that the recurrent Spergen fauna is mainly to be found. A long list of these species is given in my 1917 report. Careful study of these Gasper specimens shows that most of them had changed very little from their ancestors in the Lower Sainte Genevieve and Spergen oolites. They are therefore of only limited value in determining precisely the age of the rock in which they are found. As a rule, however, the several occurrences are accompanied by more decisively characteristic fossils. Among the latter the calyces of species of *Pentremites* have proved the most serviceable and reliable in my work. The long-based forms with flat interumbulacral areas, which commonly occur in the Gasper oolites, are never found in the older oolites.

The lithologic character and faunal peculiarities of the locally distributed upper shaly beds of the Gasper in western Kentucky have already been mentioned a few pages back in discussing the Paint Creek formation of Illinois, which it is quite evident corresponds at least essentially to the Upper Gasper of Kentucky.

The sections in southeastern Kentucky and northern Alabama.—Two other sections shown on the chart remain to be considered. These are much alike in essential features, although the one gives the facts as known in southeastern Kentucky and the other shows the sequence of beds found 200 miles to the southwest, in the vicinity of Huntsville, Alabama. In both sections the Cypress sandstone and the succeeding Golconda shale, which overlie the Gasper limestone, are thin, and either one or both may be wholly wanting or at least unrecognized in the commonly narrow interval between the Gasper and the unmistakably characterized overlying Glen Dean limestone. Here and there in the intervening area of Tennessee a similarly thin representation of the Hardinsburg sandstone, which belongs between the Golconda and the Glen Dean, is recognized.

The main reasons for bringing these two sections into the present discussion pertain to the contents of the Sainte Genevieve part and its relations to the overlying Gasper limestone. Regarding the Gasper itself we need to say only that in both sections the Gasper contains no median shale or sandstone member, so that the formation constitutes an unbroken sequence of limestone ledges. In general, however, there is no difficulty in distinguishing the lower half or third from the remaining upper part

²⁰ Mr. Butts reports finding north of Cerulean a layer of limestone in the Lower Gasper in which specimens of this genus are abundant. As none were collected, we have no means now of determining the specific relations of these remains.

by differences in their respective faunas. It is to be noted further that the break between the Gasper and the underlying Sainte Genevieve also is not very clearly defined. In fact, to succeed in making this separation one must use very detailed methods in distinguishing closely allied fossils and employ both physical and organic criteria only too commonly neglected or unappreciated by paleontologists and stratigraphers. Moreover, the Sainte Genevieve in these sections also is indivisible by ordinarily employed lithological criteria. One sees nothing of the Rosiclare, the Cypress, or the Sample sandstone, which have proved such valuable indicators in subdividing this mass of limestone in western Kentucky. In consequence the whole interval between the Saint Louis below and the Cypress sandstone above have in these sections nothing upon which the observer who is not specially trained in Chester paleontology and stratigraphy can seize and rely upon in determining the exact age of any part of this series of interbedded oolitic, crystalline, and compact limestones. To meet this condition I proposed the term Montesana limestone for the whole mass, the term to be used in the sense of a group where its subdivision is rendered practicable by punctuating beds of sandstone or shale, and as a simple formational designation where such dividing beds are absent.

The practice of most paleontological stratigraphers who have made any effort to divide the Montesana as developed in south central and eastern Kentucky, in Tennessee, in northern Alabama, and in the western edge of the southern part of the Appalachian Valley as far north as Big Stone Gap, in Virginia, has been to draw the base of the Gasper as far down in the section as the first observed appearance of a single fossil species, namely, the well-known crinoid *Platycrinus huntsvillae*. If the observer happens to hold the views espoused by Weller, who classifies the Sainte Genevieve with the Meramec group, and hence with the Iowa series, which, according to Weller's new classification,²¹ includes all of the Mississippian beneath the Aux Vases sandstone, the boundary thus decided upon forms at the same time also the base of the Chester series. However, to any one whose experience has taught him something of the gregarious habits of crinoids, the highly uncertain nature of the results obtained by this procedure is at once apparent.

Local occurrence of crinoid colonies.—Recent experience in searching for crinoids in northern Alabama will serve as an appropriate illustration. About the middle of the last century Troost listed an undescribed

²¹ Stuart Weller: The Chester series in Illinois. Jour. Geology, vol. xxviii, 1920, p. 408. Geology of the Golconda quadrangle. Kentucky Geol. Survey, series 6, vol. 4, 1921, p. 13.

crinoid under the name *Platycrinus huntsvillæ*. In 1897 Wachsmuth and Springer resurrected this name, and on the basis of hundreds of complete heads found by the senior author near Huntsville, Alabama, gave a full description with many illustrations of this variable and stratigraphically most important species. Several visits to localities in the vicinity of Huntsville made by me in the past 20 years had failed to disclose a single complete head of this crinoid. In the meantime, however, I had studied the large Wachsmuth collections from the Montesana limestone of that region now in the Springer collection of the U. S. National Museum. These studies, particularly of the slabs showing associated fossils, led me to the belief expressed in my 1917 Kentucky report, that the zone from which the bulk of the material of the *Platycrinus* was taken corresponds in age to some part of the Upper Ohara of western Kentucky. This conclusion has been combated both by implication and direct statement by others who have worked on Chester problems. The necessity of acquiring more definite information regarding the position of this *Platycrinus* zone in the Alabama section being recognized, it was decided to make another visit to this locality during the past summer. Accordingly, and on this occasion better prepared by data as to the location of the collecting grounds supplied by Doctors Springer and Kirk, the latter of whom had accompanied Mr. Wachsmuth on his last visit to them, we—that is, Messrs. Butts, Mesler, and myself—made a special trip to Huntsville in June of the present year. The information in hand mentioned as a favored spot a hill about eight miles south of Huntsville, on the road to Whitesburg. Arriving at the designated spot, we found two hills—one to the east, the other on the west side of the road. The one on the east being the more rocky, we decided to try it first. It required but a short climb to bring us to a bench made by a 5- or 6-foot bed of shaly limestone, which alone of all the exposures in this hill reminded us, in its lithologic character, of the concerned crinoid material in the National Museum.

Our search of this outcrop, though very thorough, failed completely to reveal even a fragment of *Platycrinus*. Almost discouraged, we decided to try the hill on the west side of the road. In less than a minute after reaching the level that we had searched so carefully over more than a mile of exposure on the other hill, one of us let out a yell of discovery. *Platycrinus huntsvillæ* and other crinoids were present in abundance. We had succeeded in fixing the position of the crinoid zone in the section!

Two other pertinent illustrations may be given that similarly show the local occurrence of fossil crinoids and blastoids that were not subjected to much wave action and rolling on beaches. Both concern species that have an important bearing on the questioned classification of the Sainte Genevieve limestone and the vertical range of *Platycrinus huntsvillæ*.

The first was observed with Mr. Butts in making the section south of Somerset, Kentucky—number 4 of the chart. At Cedar Grove station, about 5 miles south of Somerset, is a large quarry, mainly in the upper 30 feet of the Sainte Genevieve limestone. Above this the quarry cuts some 15 or 20 feet of Lower Gasper. At the top of the Sainte Genevieve is a 3- to 4-foot bed of yellowish argillaceous limestone which weathers to a marly clay or shale. Under this is a subcrystalline and oolitic ledge varying from 3 to 4 feet in thickness within the length of the quarry. Beneath this again is a clayey limestone like the one at the top of the formation. The two clayey layers are practically unfossiliferous; the intervening crystalline limestone also is nearly barren of specifically determinable remains. However, after prolonged search, a few specimens of *Pentremites princetonensis* and a young example of *P. buttsi* were found in the crystalline layer at the north end of the quarry.

Leaving the quarry, we proceeded northward along the railroad track a third of a mile to a low cut and then to a second somewhat deeper cut. Both cuts expose the three top beds of the Sainte Genevieve, maintaining their respective characteristics as in the quarry except in two features: First, the somewhat oolitic middle bed increases in thickness first to about 10 feet and in the second cut to nearly 20 feet. The second difference is that in both cuts this massive bed is simply crowded with small *Pentremites*, *Mesoblastus*, and *Talarocrinus*. Indeed, through streaks of a foot or more in thickness, these remains constitute approximately half of the rock-mass. Such near-by prodigality would never be suspected from an examination of the quarry face and adjacent natural exposures. Moreover, neither in the quarry nor in the railroad cuts did we see a sign of *Platycrinus*. If we had depended here on the first occurrence of remains of the *Platycrinus*, it is hard to say where the boundary between the Gasper and the Sainte Genevieve would have been drawn.

The other case is concerned with an exceedingly important association of whole crinoids that were found in Owen County, Indiana, by an amateur collector, Mr. Alva Schaefer, in a small exposure of Upper Sainte Genevieve limestone at a country post-office then known as Mill Grove. These crinoids, together with many other beautiful specimens from other formations and localities in southern Indiana, were presented three years ago by the collector to the U. S. National Museum and turned over to me for study. Recognizing the importance of this collection in the solution of problems pertaining to disputed correlations of Lower Chester formations, I planned and carried out a visit to the concerned locality. Mr. Butts, who also is interested in these questions, accompanied me. After considerable difficulties, owing to changing of place names, we found the outcrop from which the crinoids must have been

collected. We found the same kinds of *Pentremites*, shells, and corals—one of the last so far observed only at this place—in precisely the same kind of rock as in the collection donated to the Museum, but we found no heads of crinoids and only a few pieces of their columns. Evidently the collection made here by Mr. Schaefer represented, as is the rule with crinoids, merely a small and little disturbed original colony, the riches of which were completely exploited at the time of its discovery by the collector.

Upper Ohara fossils in Sainte Genevieve limestone south of Somerset, Kentucky.—Proceeding with the discussion of the sections, the feature that I wish particularly to bring out in the one to the south of Somerset, Kentucky, is the fact that here at least the Sainte Genevieve limestone includes beds at the top that contain unquestioned and, indeed, so far as present knowledge goes, unquestionable Upper Ohara fossils. Of the appended list of species found in these beds it doubtless will suffice to mention *Talarocrinus dewolfi*, *T. buttsi*, *Pentremites princetonensis*, *P. immaturus*, *P. buttsi*, and *Mesoblastus glaber*. Four of these six species are wholly unknown to me in beds older than the Upper Ohara, and the remaining two are constantly associated with them in western Kentucky and southern Illinois.

The following fossils were taken from top beds of the Sainte Genevieve limestone in a quarry at Cedar Grove and in cuts one-fourth to one-half a mile north, along the Cincinnati Southern Railroad south of Somerset, Kentucky:

<i>Triplophyllum spinulosum</i>	<i>Girtyella indianensis</i>
<i>T.</i> <i>spinulosum</i> ? small var.	<i>G.</i> <i>brevilobata</i>
<i>Pentremites princetonensis</i> — by the million	<i>Productus pileiformis</i>
<i>P.</i> <i>pulchellus</i>	<i>Diaphragmus montesana</i>
<i>P.</i> <i>buttsi</i> (young)	<i>Composita trinuclea</i>
<i>P.</i> <i>immaturus</i> ?	<i>Cleiothyridina sublamellosa</i>
<i>Mesoblastus glaber</i> — very abundant	<i>Spirifer</i> cf. <i>bifurcatus</i>
<i>Dizygocrinus persculptus</i>	<i>S.</i> cf. <i>breckenridgensis</i>
<i>Talarocrinus buttsi</i>	<i>Bellerophon</i> cf. <i>sublævis</i>
<i>T.</i> <i>dewolfi</i>	<i>Straparollus quadricolvis</i>
<i>Dichocrinus</i> cf. <i>girtyi</i> , with two long basals, flaring at junction with column	<i>Euomphalus similis</i>
<i>Dielasma</i> sp.	<i>Pleurotomaria</i> aff. <i>subglobosa</i>
	<i>P.</i> sp.
	<i>Orthoceras</i> sp.—long, slender form.

This fossil evidence, I venture to say, will be accepted as substantiating the opinion expressed by me in 1917, that in its eastward and southward extension from western Kentucky the shaly upper beds of the Sainte Genevieve are gradually replaced by thinner deposits of purer and largely

oolitic limestone in which the characteristic fossils of the Upper Ohara member either failed to exist, except locally, or, as seems the more probable, they were broken into unrecognizable fragments by wave action. Accordingly, the more eastern and southern facies of the formation do not represent merely the Fredonia member of the Sainte Genevieve limestone, but rather the whole of the formation. It is, therefore, inaccurate to employ the term Fredonia to the formation as developed in Kentucky east of Christian County, and in Tennessee, Virginia, and Alabama, in all of which areas the Rosiclare sandstone that separates the Fredonia member from the Ohara member is wanting. Instead of Fredonia we should use the name Sainte Genevieve limestone.

The section near Huntsville, Alabama—Details of the section.—Regarding the section in the vicinity of Huntsville, Alabama, which in all essential features is surprisingly like the Somerset section, the features that I shall mainly emphasize concern (1) the position of the most prolific of the *Platycrinus huntsvillæ* beds and (2) the other fossils that occur associated in the same bed with it. The details of the Sainte Genevieve and Gasper parts of the section, which is continued upward in Montesana to well into the overlying Lower Pennsylvanian sandstone, are as follows:

Detailed Section of the Montesana Limestone Group in Hills 8 Miles south of Huntsville, Alabama

	Feet
Hartselle sandstone, about 12 feet, succeeded by a small thickness of sparingly fossiliferous shale thought to represent the Golconda.	
Montesana group.	
Gasper limestone.	
Calcareous shale full of fossils; Archimedes very abundant; also other Bryozoa, Pentremites, and among the Brachiopoda <i>Chonetes chesterensis</i> in typical form.....	15
Limestone, rather massive, some ledges fine grained, others either subcrystalline or oolitic, all more or less sparingly fossiliferous	35
Shaly and highly siliceous layer; under the weather liberates great numbers of well preserved silicified Pentremites and crinoids of characteristic Gasper species.....	1
Limestones of usual Gasper types, fossiliferous but giving few good specimens.....	19
Limestone mostly in heavy ledges, some of them oolitic, with a thin layer at top full of the dismembered plates of a low-based species of Agassizocrinus, a cherty coral-bearing ledge, with <i>Lithostrotion</i> sp. and <i>Cyathophyllum</i> sp. in the lower half, and beneath this a thick basal layer containing <i>Pentremites pyramiformis</i> and large crinoid columns.....	30
Total thickness of Gasper limestone.....	100

Sainte Genevieve limestone.

Feet

Ohara member.

Limestone, rather massive and impure, gray, varying in thickness, with few recognizable fossils, among them the thickened support of a species of <i>Lyropora</i> like <i>L. quincuncialis</i> or <i>L. ranosculum</i>	4-8
Calcareous shale and argillaceous limestone, with abundant and well preserved, though fragmentary, remains of <i>Platycrinus huntsvillæ</i> , especially in the upper 6 inches.....	4-6
Limestone, semioolitic, containing usual Sainte Genevieve <i>Pentremites</i>	1-5
Shaly limestone with Ohara fossils and locally in basal foot colonies of crinoids preserving calyx and arms.....	0-1

Fredonia member.

Oolitic and fine-grained light-colored limestone, usually in thick ledges, with considerable chert 15 to 30 feet beneath top; fossils of kinds usually found in this member, but not very plentiful, to base of Chester series and to top of underlying Saint Louis limestone, about.....	125
---	-----

Total thickness of Sainte Genevieve limestone, about..... 150

Though some doubtless will find it difficult to locate exactly the boundary between the Sainte Genevieve and Gasper limestones in the hills to the east and south of Huntsville, Mr. Butts and I experienced little trouble and agreed perfectly in recognizing the line of contact between them. It is simply a matter of knowing what to look for and where to look for it. Immediately beneath the Gasper, as indicated in the detailed section, is a bed of solid gray limestone varying greatly in thickness in different places, sometimes absent entirely and in one exposure varying from less than 4 feet to 8 feet. It is only sparingly fossiliferous and the fossils observed are imperfect and badly preserved. However, we welcomed one find, the U-shaped thickened support of a *Lyropora*, that at once suggested the top zone of the Ohara in western Kentucky and with the other data procured here seemed a veritable cap sheaf to the evidence on which I have now convinced myself that the Sainte Genevieve limestone here, as in western Kentucky, not only includes representatives of the Upper Ohara, but that the same species of *Dizygocrinus* and *Platycrinus* that I claimed to have found in the Upper Ohara near Princeton, Kentucky, occur also in Alabama practically to the top of the beds which I am correlating with the Upper Ohara. We found not only *Dizygocrinus* and *Platycrinus huntsvillæ* in these upper beds, but associated on the same slabs is "*Globocrinus*" *unionensis*, which Weller, no less than I, regards as a guide fossil of the Upper Ohara in western Kentucky and southern Illinois. The same slabs also contained a number

of other crinoids that were determined by Mr. Springer as indistinguishable from supposed Renault species and were so listed in my 1917 report. To that list I can now add another species, namely, the very peculiar *Catillicrinus carpenteri* (Wachsmuth and Springer).

The common occurrence of *Platycrinus huntsvillæ* in association with supposed Renault species of crinoids, hence with unquestioned Chester fossils, is thus established as an indisputable fact in Alabama; and it is probably true, as I have claimed, also for western Kentucky; but I wish to record the corroborating fact that the crinoid fauna previously mentioned as from the Upper Sainte Genevieve in Owen County, Indiana, is precisely the same fauna, including the *Platycrinus*, that was collected long ago in the vicinity of Huntsville, Alabama, by Wachsmuth and his associates and which was stratigraphically fixed by my associates and me during the past summer. That this Upper Ohara fauna retains its characteristic aspect from Huntsville, Alabama, to Owen County, Indiana, is shown by the following lists:

The following fossils were obtained from cherty lenses just beneath the main crinoid zone near the top of the Sainte Genevieve limestone, 8 miles south of Huntsville, Alabama:

<i>Belemnospongia</i> n. sp.	<i>Productus inflatus</i>
<i>Zaphrentis</i> (<i>Triplophyllum</i>) <i>spinulosum</i>	<i>Echinoconchus genevievensis</i>
<i>Michelinia</i> aff. <i>princetonensis</i> , but nearer an undescribed Middle Chester variety	<i>Spirifer breckenridgensis</i>
<i>Fenestella cestriensis</i>	<i>Spirifer</i> cf. <i>pellænsis</i> and <i>increbescens</i>
<i>Chonetes chesterensis</i> var. <i>grandis</i> n. var. Larger than the typical variety, the hinge line commonly an inch in length, with 7 or 8 spines on each side of beak; striæ fine, about 145 on each valve; ventral valve with broad shallow median sinus.	<i>Dielasma arkansanum</i>

The Chester aspect of this small faunule is striking. It is suggested particularly by the Brachiopoda. The *Chonetes* is abundant.

Lists of fossils from the Huntsville area.—The following fossils were obtained from a shaly limestone (crinoid beds) near the top of the Sainte Genevieve limestone, in hills 8 miles south of Huntsville, Alabama:

Concentrically lined disk-shaped sponge.	<i>Productus ovatus</i>
<i>Triplophyllum spinulosum</i>	<i>Productus inflatus</i>
<i>Mesoblastus glaber</i>	<i>Diaphragmus montesana</i>
	<i>Pustula genevievensis</i>

- Pentremites princetonensis*, two varieties
Pentremites pulchellus, three varieties
Pentremites tuscumbia
Platycrinus huntsvillæ and 14 other crinoids listed separately in a following table
Stenopora tuberculata
Fistulipora sp.
 Ten or more other Bryozoa, all of them common in the Upper Ohara zones in western Kentucky
Orthotetes kaskaskiensis
Rhipidomella cf. *dubia* (same in Upper Ohara of western Kentucky)

The following fossils were obtained from the top beds of the Sainte Genevieve limestone in a quarry and natural exposures at Mill Grove, Owen County, Indiana:

- | | |
|--|--|
| <i>Triplophyllum spinulosum</i> | <i>Fenestellidæ</i> , five or six species usually found in both upper and lower members of the Sainte Genevieve. |
| <i>Lithostrotion</i> n. sp. aff. <i>proliferum</i> | <i>Spirifer pellænsis</i> |
| <i>Pentremites pulchellus</i> | <i>Spirifer breckenridgensis</i> |
| <i>Pentremites princetonensis</i> | <i>Composita trinuclea</i> |
| <i>Pentremites princetonensis</i> (elongate variety) | <i>Cliothyridina sublamellosa</i> |
| <i>Pentremites immaturus</i> | <i>Pugnoides ottumwa</i> |
| <i>Platycrinus huntsvillæ</i> and 15 other crinoids listed separately in the following table | <i>Bucanopsis</i> aff. <i>textilis</i> |
| <i>Stenopora</i> cf. <i>ramosa</i> | <i>Orthonychia</i> cf. <i>acutirostra</i> |
| <i>Cæloconus rhombicus</i> | <i>Euomphalus</i> aff. <i>planus</i> |
| | <i>Helodus</i> sp. and five other kinds of fish teeth. |

Species and geographic distribution of the Upper Ohara crinoid fauna.—The following tabulated list of Upper Ohara crinoids shows the wide distribution and practical unity of this crinoid fauna from Huntsville, Alabama, to Owen County, Indiana, and Monroe County, Illinois. In the columns on the right of the list the presence of the species at each of the mentioned localities is indicated by a cross. The list is based on collections in the U. S. National Museum, the specimens found at Huntsville and near Burksville, Monroe County, Illinois, belonging to the Springer Collection. The specific identifications were all made by Dr. Frank Springer. The crinoid bed near Burksville was pointed out to Doctor Springer's collector by Professor Weller as belonging to his Renault formation.

Table indicating Composition and geologic Distribution of the Ohara Crinoid Fauna

	Huntsville	Owen County	Burksville
<i>Dizygocrinus superstes</i> Ulrich.....	x	x	x
<i>Dizygocrinus</i> (<i>Globocrinus</i>) <i>unionensis</i> (Worthen).....	x	x	x
<i>Platycrinus huntsvillæ</i> W. and Sp.....	x	x	
<i>Onychocrinus distensus</i> M. and W.....	x	x	x
<i>Tarocrinus huntsvillæ</i> Springer.....	x	x	
<i>Catillocrinus carpenteri</i> (Wachsmuth)....	x	x	x
<i>Vasocrinus</i> sp.....	x		x
<i>Pachylocrinus propinquus</i> (Worthen)....		x	x
<i>Pachylocrinus salteri</i> (Worthen).....		x	x
<i>Pachylocrinus scoparius</i> (Hall).....	x	x	x
<i>Pachylocrinus sculptus</i> (Worthen).....	x	x	x
<i>Pachylocrinus spinobrachiatus</i> (Worthen)	x	x	x
<i>Pachylocrinus venustus</i> (Worthen).....		x	x
<i>Scytalocrinus decabrachiatus</i> (Hall).....	x	x	
<i>Scytalocrinus</i> , small species (? new).....	x	x	
<i>Decadocrinus</i> , large species (? new).....	x	x	
<i>Culmicrinus</i> aff. <i>missouriensis</i> (Shumard)	x	x	
<i>Camptocrinus cirrifer</i> W. and Sp.....	x		x

I have never seen any specimens of *Platycrinus* from rocks older than the Sainte Genevieve limestone that I could not at once distinguish from the several varieties commonly united under the name *P. huntsvillæ*. Accordingly, then, I regard this *Platycrinus* as a characteristic Lower Chester fossil, and I apply the same designation to the other crinoids with which it is associated in the Upper Ohara of Alabama and Indiana and in part already in the lower, or Fredonia, member of the Sainte Genevieve limestone in western Kentucky.

Age of the crinoid bed near Burksville, Illinois.—To paleontologists who hold views like mine, the extraordinary similarity that obtains, as shown in the foregoing table, between the crinoid fauna of the beds at Huntsville, Alabama, in Owen County, Indiana, and in the typical Upper Ohara in Caldwell County, Kentucky, and that which is found near Burksville, Illinois, in beds hitherto credited to the Renault formation is highly suggestive of some error in the age assignment of the latter. If the facts in the case are actually as reported, I can view the resulting condition only as highly disappointing. I have maintained, namely, that in the evolution of organisms of multipartite composition and generally complex structure, even relatively short periods, geologically speaking, intervening between the first and second and between each of the succeeding appearances of such types in the sequence of accessible sedimentary marine deposits must be indicated by more or less clearly recogniz-

able changes in the combination of the parts. Organisms are forever either striving for improvement in their life processes or they are subjected to changing conditions that require modification in their habits and physical characteristics; and these relatively normal modifications, whether acquired through optional or enforced conditions, are supplemented over and over again by more purely accidental impositions and by peculiarities and tendencies inherited from both immediate and more remote ancestors.

The Crinoidea would seem to include especially favorable illustrations of the principle. One would expect it to be illustrated particularly by such species of the class as have arms that are frequently and variously divided and at regular intervals, arms that zigzag in some and are nearly straight in others, with variously, but in each species regularly, disposed nodes on their joints, or have variously arranged ridges, nodes, pits, and other features on both the dorsal and ventral surfaces of their calyces. Therefore, if we accept the occurrence of a practically unchanged reappearance of the Upper Ohara crinoid fauna in the Renault in Monroe County, Illinois, as an indisputable fact, one can hardly escape the alternative convictions that either the time that elapsed between the dates of the two crinoid zones—that is, the time consumed in the deposition of the intervening Aux Vases sandstone plus the times represented by the supposed breaks between this sandstone and the formations lying immediately beneath and above—was too short to make any appreciable change in this fauna, or the crinoids in this instance maintained their characteristics, both as regards their structural peculiarities and their associates in making the fauna, with uncommon persistence.

Neither of these conclusions seems satisfactory. The time most probably was long enough to bring about very considerable changes, not only in the composition of the fauna, but also in the characters of the species themselves; and it seems unreasonable and unwarranted by any known facts to assume that these in large part highly specialized crinoids were so much more stable than usual. Under the circumstances, I can not avoid the suspicion that there is something wrong about the age assigned to the Monroe County crinoid bed that contains so many species which elsewhere are found only in upper members of the Sainte Genevieve limestone. The only kind of evidence that under my present view as to the essential coterminity of the Sainte Genevieve in Missouri, Illinois, Indiana, Kentucky, and Alabama I can accept as proving the distinctness of the Monroe County and the Huntsville crinoid zones is the presence of the Aux Vases sandstone beneath the crinoid zone in Monroe County.

It is a well known fact that the Aux Vases sandstone is not continu-

ously developed in Monroe County. Locally, as to the north or northeast of Prairie du Rocher, it is wanting where it would be if present. Now, I have no information regarding this sandstone at the supposed Renault crinoid locality which lies about 3 or 4 miles to the southeast of Burksville; but this place is not far off the line on which the Aux Vases is locally wanting, so that the true Renault rests directly on older formations. Perhaps this is the case at the crinoid locality. If so, then this crinoid bed may not be Renault in age, but pre-Aux Vases, which would help paleontological correlation very greatly.

This suggestion may prove in error, but in the meantime there is much in favor of it besides the direct testimony of the crinoids themselves. (1) So far as I know, none of these crinoids occur in exposures of the typical Renault that are underlaid by Aux Vases sandstone. (2) The material in the Springer Collection from the locality southeast of Burksville contains only one species of *Talarocrinus*, and this I have not succeeded in distinguishing from the Shetlerville variety of *T. trijugis*, whereas it does seem to differ from all of the three or four species of the genus that I have collected from unquestioned outcrops of the Renault. (3) *Platycrinus huntsvillæ*, which is rare in the Upper Ohara of Kentucky and Indiana and probably failed entirely before reaching Illinois, does not occur in the questioned Monroe County Renault collections available to me, but *Dizygocrinus persculptus*, which I based on specimens from the Sainte Genevieve limestone in western Kentucky, does occur in the Monroe County collections as well as in those from the Upper Sainte Genevieve of Indiana, Kentucky, and Alabama, in all of which it is associated with the *Platycrinus*. (4) The genus *Pentremites* is but sparingly represented in the questioned Renault of Monroe County, and the few specimens present are not of kinds found in the true Renault of Missouri or like those commonly met with in the Lower Gasper of Kentucky, but rather of Ohara forms. Finally (5) none of the other classes of fossils that are associated with the crinoids at the questioned Renault locality include anything that might not be expected in an Upper Ohara zone as well as in one of post-Aux Vases age.

In my 1917 report (page 181) I listed 9 species from the vicinity of Huntsville, Alabama, as Gasper oolite fossils, with the statement by Doctor Springer that he has "all of these species also from the Renault formation in Monroe County, Illinois." At that time I had no reason to doubt the age of the crinoid bed near Burksville to which Doctor Springer's statement refers. Besides, the position of the crinoid beds in the Huntsville section was not exactly known. Indeed, it was believed that crinoids like those in the supposed Renault of Monroe County oc-

curred in two similar but distinct zones—one with the *Platycrinus*, the other without it and higher, presumably in the Gasper part of the Montesana limestone. The work of the past summer shows that there is only one zone, and that the supposed Gasper crinoids occur, like those listed in 1917 as found on the same slabs with *Platycrinus huntsvillæ*, in the main *Platycrinus* zone, which lies only a few feet beneath the base of the Gasper.

CONCLUSIONS

With a single non-essential amendment and certain added facts, the "concluding statement" in my 1917 Kentucky Report (page 190) will do as well for this paper. As revised, it reads as follows:

"In the foregoing pages I have applied and verified means of correlating geological formations—correlation by stratigraphic position, by lithologic similarity, by sequence of like lithologic units, faunas, and geologic events, by paleogeographic probabilities, by evolutionary stages of species and faunas, by comparison of generalized faunal aspects, and by the more direct and precise matching of faunas, species, and particularly of systematically subordinate mutations of complexly constructed organic remains. The result in each trial has been as definite as the particular means employed permitted, and in every instance the predominant trend of the evidence has been clearly and uniformly favorable to the views here advocated. Such continuous corroboration would be impossible if my conclusions were not firmly grounded on incontrovertible facts and, in essential respects, absolutely true.

"Whereas the relatively generalized criteria chiefly relied on hitherto may have left some room for legitimate argument, the more definite and positive nature of most of the new data presented in this paper has destroyed all chance for logical and successful refutation. So far as it may be done with the material and methods available, the case [referring to the base of the Chester series, the inclusion of the Upper Ohara in the Sainte Genevieve formation, and the age relations of the Upper Ohara to the Renault] is settled. It can be unsettled again only by discrediting paleontological evidence in correlation; but that would be nothing short of stratigraphical suicide, for after all it is on the fossils that we mainly rely in establishing the time relations of geological events. If paleontological correlations have sometimes proved erroneous or imperfect, the fault has not lain with the fossils, but with the paleontologist who endeavored to interpret their testimony. Studied in minutest detail and determined and matched as critically as possible, the fossils tell the story both truly and fully.

"I have conscientiously endeavored to fulfill these requirements in the present case; and I claim, therefore, that in all essential respects the conclusions reached are in harmony with the facts:

"(1) The upper Gasper corresponds to the Ridenhower shale, and both to the Paint Creek formation. (2) The lower Gasper represents the Renault formation, and the sandstone directly beneath the Gasper is the correlative of [or, rather, occupies the same position in the section as] the Aux Vases sand-

stone which underlies the Renault. (3) The top of the Ohara is older than the Aux Vases [or the Bethel] sandstone and consequently no part of it can be of the age of the Renault. [And if the Renault actually corresponds, as every one concedes, to the Lower Gasper, which overlies the Bethel sandstone, it can not also correspond to any part of the Upper Ohara which entirely underlies the Bethel.] (4) The lower and middle parts, at least, of the Ohara most probably are represented in the Sainte Genevieve limestone in the Mississippi Valley and also in the Sainte Genevieve part of the Montesana limestone in Alabama. (5) The faunas of the Ohara and Fredonia members of the Sainte Genevieve limestone are more closely related than had been supposed, and the relationship is sufficiently binding to require their classification in the same group and series. [To which we may add the now definitely established facts: (a) that *Pugnoides ottumwa*, *Platycrinus huntsvillæ*, and *Dizygocrinus superstes* are not confined to Sainte Genevieve beds beneath the Upper Ohara, but pass upward into and perhaps beyond the top of the Upper Ohara; (b) that *Cystodictya labiosa* and *Amplexus geniculatus* are not confined to the Upper Ohara, the former being found also in the Fredonia and again in the Gasper, the latter being known in Kentucky and apparently also in Union County, Illinois, in the middle part of the Gasper; and (c) that the species of *Talarocrinus* in the typical Renault are at least partly the same as those in the Lower Gasper, but none of these two sets of species is precisely like any of the three species of this genus that are found in the Upper Ohara.] (6) The number of fossils held in common by the Fredonia and the Saint Louis limestone is relatively small. (7) The most effective and the most widely displayed of the physical breaks in the upper Mississippian rocks is the one at the top of the Saint Louis limestone. (8) The boundary between the Meramec and the succeeding series is most naturally and most conveniently drawn at the probably everywhere unconformable contact between the Saint Louis and the Sainte Genevieve limestones."

These conclusions can not be denied and finally expunged by innuendo, by implications of carelessness in collecting or of incompetence in determining geologic horizons, or by negation based on the mere failure of my critics to find the fossil species at the places and in the beds in which I found them.

INDEX TO VOLUME 33

	Page
ABLATION of the eastern lobe of the Wisconsin ice-sheet; J. H. Cook...	117
ADAMS, L. H.; A source of heat in volcanic activity.....	144
AFRICA, Mineral genesis in South.....	229
AFTER-EFFECTS of igneous intrusion; Presidential address by J. F. Kemp	231
AGE and development of Red Beds and the terrestrial vertebrates in the Appalachian and the Kansas-Texas region; J. W. Beebe.....	208, 671
— of the coal beds of the Kaiping coal basin in northeastern China; A. W. Grabau	201
— — Talladega phyllite; W. F. Prouty	151
ALABAMA, Ordovician of.....	605
—, Volcanic ash bed in the Ordovician of	152
ALASKA, Kennecott glacier of.....	527
ALGONKIAN sediments, Quantitative study of.....	108
ALLEN, E. T.; Hot springs of Lassen National Park.....	141
— and A. L. DAY; Recent eruption of Lassen Peak.....	141
ALLING, H. L.; Petrographic studies of some New York sediments.....	107
ALTAMONT moraine.....	102
ALTURAS, California, Tertiary mammalian remains from.....	188
AMERICAN Association for the Advancement of Science, Greetings from Section E of.....	135
AMMONITES, Methods of studying.....	209
AMPHIBIAN from the Coal Measures of Kansas	212
AMYGDALOID from Nova Scotia.....	126
ANALCITE from Nova Scotia, with a discussion of analcite analyses in general; A. L. Parsons.....	230
ANDEAN geosyncline.....	90
ANDES between Cochabamba and Santa Cruz, Reconnaissance of the.....	553
—, Front ranges of the.....	138, 703
—, Reconnaissance of eastern.....	124
ANDROSCOGGIN River, Former courses of the.....	121
ANTEVS, E.; Recession of the land-ice in New England.....	86
ANTHRACITE of Pennsylvania, Organization of.....	149
ANTIMONY mines of Shiu Chow, China; G. D. Hubbard.....	149
APPALACHIAN Coal Measures.....	111
—, Red Beds and vertebrates of.....	671
— terrestrial vertebrates.....	208
ARÆOCYON, a probable old world migrant; M. R. Thorpe.....	214
A RECENT hot-spring deposit in Bolivia; W. Lindgren.....	224
ARGENTINA, Front ranges of the Andes of	138, 703
ARIZONA, Silver ores near Wickenburg.	225
ARNOLD, RALPH; Hazards of the oil industry	225
ASHLEY, G. H.; Proposed new nomenclature of the Appalachian Coal Measures	111
A SOURCE of heat in volcanic activity; L. H. Adams.....	144
A STUDY of crystal symmetry; A. F. Rogers	229

	Page
A SUGGESTION for the terminology of certain ore deposits; W. Lindgren.	224
AUDITING Committee, Election of.....	12
— of Paleontological Society, Appointment of.....	195
—, Report of the.....	113
BALL, S. H.; Geological and geographical occurrence of precious stones.	226
—, Secretary; Proceedings of the First Annual Meeting of the Society of Economic Geologists, held at Amherst, Massachusetts, December 28-30, 1921.....	223
BASALTS, Deccan traps and other plateau	146
— of India.....	765
BASIN Range faults, Morphologic changes in.....	96
BASSLER, R. S.; Mohawkian and Cincinnati rocks of central Tennessee.	207
—, Secretary; Proceedings of the Thirtieth Annual Meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921.....	191
BASTIN, E. S.; Primary native silver ores near Wickenburg, Arizona, and their bearing on the genesis of the silver ores of Cobalt, Ontario.....	225
—; Stressing economics in the teaching of economic geology.....	224
— and W. LINDGREN; Geology of the Braden mine, Chile.....	224
BATEMAN, A. M.; Kennecott glacier of Alaska	527
BEEBE, J. W.; Age and development of Red Beds and terrestrial vertebrates of the Appalachian and Kansas-Texas region.....	208, 671
BIBLIOGRAPHY and catalogue of the fossil vertebrates of North America	203
BIG Badlands of South Dakota, Oreodon beds of the.....	155
BIG STONE gap area, Pre-Pennsylvanian rocks of the.....	98
BLACK Hills, Cumingtonite schists of.	225
— shales of Ohio.....	152
BLASTOMERYX, Restoration of.....	211
BOLIVIA, Front ranges of the Andes of.	138, 703
—, Recent hot-spring deposit in.....	224
—, Reconnaissance of the Andes between Cochabamba and Santa Cruz	124
BOSSLER, R. B.; Results obtained by improved methods of extracting petroleum	224
BOWIE, W.; Theory of isostasy—a geological problem.....	113, 273
BOWLES, O.; Plea for economic mineralogy	229
BOYDELL, H. C.; Some etching tests of pyrrhotite	226
BOWEN, N. L.; Genetic features of alnoitic rocks from Isle Cadieux, Quebec	130
—; Two corrections to mineral data...	230
BOWEN, W. C.; Petrographic notes on the Franklin, New Jersey, zinc ores	225
BRADEN mine, Chile.....	224
BRANSON, E. B.; Geology of Costa Rica	90

	Page		Page
BRIONES formation of middle California	189	CLARK, T. H.; Devonian limestone at Saint George, Quebec.....	201
BROWN, B., and MARJORIE O'CONNELL; Correlation of the Jurassic formations of western Cuba.....	159, 639	—; Nature of <i>Salterella</i>	196
BROWN, T. C.; Flooding of oil wells by fresh water.....	151	CLELAND, H. F.; Demonstration material in geology.....	56
—; Preliminary notes on the shorelines of glacial lake Nashua, near Fitchburg, Massachusetts.....	118	—; Report of Committee on Teaching of Geology.....	55
BURIED granite in Kansas; R. C. Moore	96	COAL formation and isostasy.....	327
BURLING, L. D.; Cambro-Ordovician section near Mount Robson, western Canada	108	— Measures of the Appalachian.....	111
BURRARD, SIR SIDNEY; Folding of mountain ranges—the argument from isostasy	114, 333	COALS, Origin of.....	148
CÆRULEOFIBRITE, a new mineral; E. T. Holden	229	COBALT, New aspects of geology at.....	189
CALIFORNIA, Briones formation of middle	189	COLLOPHANE, a much-neglected mineral; A. F. Rogers.....	189
—, Differential movements in San Francisco Bay region of.....	189	COLORADO, Ore deposits of Leadville	149, 225
—, Marine Tertiary of.....	188	— River, Geology of.....	122
—, Silicates from Crestmore.....	230	COMMITTEE on Policy, Report of the Council	136
—, Tertiary mammalian remains from near Alturas.....	188	— the Teaching of Geology, Election of	15
—, Tridymite-orthoclase rock from Imperial County.....	129	— — — — —, Report of.....	55
CAMBRIAN, Life eras before the.....	107	COMPARATIVE study of the Nebraskan and Kansan tills in Iowa; G. F. Kay	115
— of Massachusetts, Oldhamia in.....	198	CONDITION of magnesite in 1920; R. W. Stone	226
— succession of northwestern Vermont; A. Keith.....	123	— the earth's crust and the earlier American gravity determinations; G. R. Putnam.....	113, 287
CAMBRO-ORDOVICIAN section near Mount Robson, western Canada; L. D. Burling	108	CONNECTICUT basin during the Newark epoch	87
CAMDEN formation of Oklahoma.....	665	—, Geology of the Guilford Quadrangle	147
CANADA, Alnoitic rocks from Isle Cadieux, Quebec.....	130	— Valley fossils.....	209
—, Cambro-Ordovician section in western Canada.....	108	CONSTITUTION and By-laws.....	162
—, Devonian limestone at Saint George, Quebec	201	— of the Ohio black shales; G. H. Chadwick	152
CANADIAN Rockies, Relation of Purcell Range to.....	91	COOK, H. J.; Tooth of almost human type from the Lower Pliocene Snake Creek beds of western Nebraska	214
CANIDÆ, Phylogeny of the.....	214	COOK, J. H.; Ablation of the eastern lobe of the Wisconsin ice-sheet....	117
CARE of museum specimens; A. L. Parsons	230	CORAL seas, Marginal belts of the....	140
CAVERN deposits in the Permian of Texas	153	CORALS, Unattached simple Paleozoic..	201
CAVES of the lower Ohio Valley repositories of mammalian and human remains	156	CORDILLERAN Section, Election of officers of.....	188
CENTRAL AMERICA, Basaltic lava from.	143	—, Twentieth Annual Meeting of the	187
CEPHALOPODS and trilobites, Possible habits of.....	197	CORRELATION and paleogeography of the marine Tertiary of California; B. L. Clark.....	188
CERTAIN marked differential movements in the San Francisco Bay region; G. D. Louderback.....	189	— of the Jurassic formations of western Cuba; B. Brown and Marjorie O'Connell	159, 639
CHADWICK, G. H.; Constitution of the Ohio black shales.....	152	CORRESPONDENT, Election of.....	13
CHANEX, R. W.; Flora of the Payette formation	203	CORRUGATED intraformational rocks....	98
— — — — — Rancho la Brea.....	204	COSTA RICA, Geology of.....	90
CHESTER formation, Facts bearing on correlation of.....	208	COTEAU DES PRAIRIES, Glacial formations on the.....	101
— formations, New facts bearing on correlations of.....	805	COUNCIL Report.....	6
CHILE, Braden mine in.....	224	CROCIDOLITE from eastern Pennsylvania; E. T. Wherry and E. V. Shannon	229
CHINA, Antimony mines of Shiu Chow.	149	CROSBY, I. B.; Former courses of the Androscoggin River.....	121
—, Kaiping coal basin of.....	201	CRYSTALLOGRAPHY of three Rhode Island minerals; A. C. Hawkins.....	229
—, Ordovician formations of north....	202	—, Use of plans and elevations in teaching	229
CINCINNATIAN rocks of central Tennessee	207	CRYSTAL symmetry, A study of.....	229
CLARK, B. L.; Correlation and paleogeography of the marine Tertiary of California.....	188	CUBA, Correlation of Jurassic formations of western.....	159, 639
		CUMMINGTONITE schists of the Black Hills	225
		CUSHING, H. P., Bibliography of.....	52
		—, Memorial of.....	44
		CUSHMAN, J. A.; Limits of variations in foraminifera.....	206
		—; Use of foraminifera in determining underground structure, especially in petroleum mining.....	145

	Page		Page
DAKOTA sandstone, Some problems connected with.....	203, 255	FEW more facts bearing on the correlation of the Chester formation; E. O. Ulrich.....	208
DAVIS, W. M.; Faults, underdrag, and landslides of the Great Basin ranges.	92	FLOODING of oil wells by fresh water; T. C. Brown.....	151
—; Marginal belts of the coral seas...	140	FLORA of the Payette formation; R. W. Chaney.....	203
—; Peneplains and the geographic cycle.....	121, 581	— — — Rancho la Brea; R. W. Chaney	204
DAY, A. L., and E. T. ALLEN; Hot springs of Lassen National Park..	141	FOERSTE, A. F.; Unattached simple Paleozoic corals.....	201
— — —; Recent eruption of Lassen Peak.....	141	FOLDING of mountain ranges—the argument from isostasy; Sir Sidney Burrard.....	114, 333
DECCAN traps and other plateau basalts; H. S. Washington.....	146, 765	FORAMINIFERA in determining underground structure, Use of.....	145
DEMONSTRATION material in geology; H. F. Cleland.....	56	—, Limits of variations in.....	206
DEVONIAN limestone at Saint George, Quebec; T. H. Clark.....	201	FORMER courses of the Androscoggin River; I. R. Crosby.....	121
— of Oklahoma, with special reference to the Oriskany and Camden formations; Chas. Schuchert.....	665	FOSSIL ammonites, Methods of studying — amphibian from Coal Measures of Kansas.....	209
DE WOLF, F. W.; Need of expediting topographic mapping of the United States.....	225	— pines of the Mesozoic.....	212
DILLER, J. S.; Surface fusion of lava..	142	— vertebrates of North America, Bibliography of.....	203
DISCUSSION of the age of the Briones formation of middle California; P. D. Trask.....	189	FOSSILS: <i>Aræocyon</i>	214
— — — Pleistocene and its vertebrate faunas; O. P. Hay.....	156	—: <i>Canidae</i>	214
DRIFT sheets of northern Illinois.....	116	—: <i>Eporeodon socialis</i> , Marsh.....	213
DUNBAR, C. O.; Environment of the early Permian insects of Kansas..	153	—: Human type of tooth from Nebraska.....	214
DUMBLE, E. T.; Recent geological work in Gulf Coast oil fields.....	207	—: Labyrinthodont footprints from Maryland Carboniferous.....	211
EAKLE, A. S.; Juruprite, a new mineral from Crestmore, California.....	188	—: Late Tertiary mammalian remains near Alturas, California.....	188
—; Probable occurrence of massive troilite in serpentine.....	188	—: Marsupial from John Day Oligocene of Oregon.....	188
—; Occurrence of monosulphide of iron —; Silicates of the contact limestones of Crestmore, California.....	229	—: <i>Merychiodontidae</i>	212
EARTH movements and isostasy.....	114, 317	—: Nature of <i>Taonurus</i>	199
EARTH'S crust, Condition of the..	113, 287	—: Restoration of <i>Blastomeryx</i>	211
EDITOR'S report.....	11	—: Upper Pawnee Creek beds.....	211
ELECTION of Auditing Committee.....	12	— from Ordovician formations of north China.....	202
— Committee on the Teaching of Geology.....	15	— the Big Badlands of South Dakota	209
— Correspondent.....	13	— of Lower Cambrian of Massachusetts	198
— Fellows.....	14	— Lower Miocene of Wyoming.....	211
— officers.....	13	— <i>Salterella</i>	196
— and members of the Paleontological Society.....	195	— the Connecticut Valley; E. L. Troxell.....	209
— for 1922 of the Mineralogical Society.....	227	— — — Great Basin and Great Plains.	210
— of Cordilleran Section.....	188	FOYE, W. G.; Geology of the Guilford, Connecticut, Quadrangle.....	147
— representatives on the National Research Council.....	15	—; Structure of the Connecticut basin during the Newark epoch.....	87
EMERSON, B. K., Presentation of loving cup to.....	134	FRANKLIN, New Jersey, zinc ores.....	225
ENVIRONMENT of the early Permian insects of Kansas; C. O. Dunbar....	153	FRONT ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina; K. F. Mather	138, 703
EVIDENCES of assimilation during the Katmai eruption of 1912; C. N. Fenner.....	129	FURLONG, E. L., and C. STOCK; Marsupial from the John Day Oligocene of Logan Butte, Oregon.....	189
EXPERIMENTAL study of the invasion of oil into a water-wet sand; O. W. Skirvin.....	224	FURTHER data on the differentiation of the glacial drift sheets of northern Illinois; M. M. Leighton.....	116
FAULT production and isostasy.....	330	GALLOWAY, J. J.; Nature of <i>Taonurus</i> and its use in estimating geologic time.....	199
FAULTS of the Great Basin ranges... 92, 96		—; Red limestones and their geologic significance.....	105
— — — Yellowstone Park plateau.....	99	—; Value of the physical characters of sand grains in the interpretation of the origin of sandstones.....	104
—, underdrag, and landslides of the Great Basin ranges; W. M. Davis.	92	GENERAL morphologic features of Basin Range faults; G. D. Louderback..	96
FENNER, C. N.; Evidences of assimilation during the Katmai eruption of 1912.....	129	GENETIC features of alioitic rocks from Isle Cadieux, Canada; N. L. Bowen	130
FELLOWS, Election of.....	14	GEOLOGICAL and geographical occurrence of precious stones; S. H. Ball.....	226

	Page		Page
GEOLOGY, Demonstration material in teaching	56	HOVEY, E. O., Secretary; Proceedings of the Thirty-fourth Annual Meeting of the Geological Society of America, held at Amherst, Massachusetts, Wednesday-Friday, December 28-30, 1921.....	1
— of Costa Rica; E. B. Branson.....	90	HOWELL, B. F.; Oldhamia in the Lower Cambrian of Massachusetts.....	198
— — Kauai, Hawaiian Islands; N. E. A. Hinds	125	HUBBARD, S. D.; Antimony mines of Shiu Chow, China.....	149
— — the Braden mine, Chile; W. Lindgren and E. S. Bastin.....	224	HUDSON and Mohawk region, Pleistocene history of.....	515
— — Colorado River in southeastern Utah; C. R. Longwell, H. D. Miser, R. C. Moore, and S. Paige.....	122	— region, Pleistocene history of.....	117
— — Guilford, Connecticut, Quadrangle; W. G. Foye.....	147	HUGE amphibian from the Upper Coal Measures of Kansas; H. A. Martin	212
— — Pawtuckaway Mountains; E. S. C. Smith.....	128	HUMAN type of tooth from Snake Creek beds of western Nebraska.....	214
GLACIAL drift sheets of northern Illinois	116	HURST, M. E.; Study of supergene processes at Neihart, Montana.....	226
— formations on the Coteau des Prairies; F. Leverett.....	101	HYRACODONS from the Big Badlands of South Dakota; W. J. Sinclair.....	209
— lake Nashua, Massachusetts.....	118	HYPOPARIAN genera of trilobites of the Ordovician	205
GLACIATION of New Hampshire; J. W. Goldthwait	86	ICE Age, Stages of the; Warren Up- ham	100, 491
GLOCK, W. S., and A. C. TROWBRIDGE; Quantitative study of the derivation of North American sediments.	108	IGNEOUS intrusion, After-effects of....	231
GOLD-BEARING cummingtonite schists of the Black Hills, South Dakota; J. J. Runner.....	225	— rock series, Graphic study of....	127, 617
GOLDTHWAIT, J. W.; Glaciation of New Hampshire	86	ILLINOIS, Glacial drift sheets of Northern	116
GRABAU, A. W.; Age of the coal beds of the Kaiping coal basin, in north-eastern China.....	201	INDEX minerals for the interpretation of geological history; J. J. Runner	230
—; Ordovician formations of north China	202	INSECTS of Kansas, Permian.....	153
GRANITE, Sillimanite-schist inclusions in	130	INTRAFORMATIONAL corrugated rocks; W. J. Miller.....	98
GRAPHIC study of igneous rock series; F. F. Grout.....	127, 617	IOWA, Nebraskan and Kansan tills in..	115
GRATON, L. C.; Probable origin of certain vein structures.....	224	—, Strata near Stuart.....	153, 689
GRAVITY observations.....	287	IRON, Monosulphide of.....	229
GREAT Basin and Great Plains fauna, Relationship of.....	210	ISOSTASY and applied geology; J. F. Kemp	114, 327
— — ranges, Faults, underdrag, and landslides of the.....	92	— — coal formation.....	327
— Plains and Great Basin fauna, Relationship of.....	210	— — earth movements; H. F. Reid	114, 317
GREETINGS from Section E. American Association for the Advancement of Science.....	135	— — fault production.....	330
GROUT, F. F.; Graphic study of igneous rock series.....	127, 617	— — oil geology.....	329
GUILFORD Quadrangle, Geology of the..	147	— — rock density; H. S. Washington.	114, 375
GULF Coast oil fields, Geological work in	207	— — the folding of mountain ranges..	114
HAWAIIAN Islands, Geology of Kauai..	125	—, Some considerations touching on	114, 303
HAWKINS, A. C.; Crystallography of three Rhode Island minerals.....	229	—, Symposium on.....	113, 273-410
HAY, O. P.; Discussion of the Pleistocene and the vertebrate faunas....	156	—, Theory of.....	113, 273
—; Supplement to the bibliography and catalogue of the fossil vertebrates of North America.....	203	ISOSTATIC compensation considered as a cause of thrusting; A. C. Lawson	114, 337
HAZARDS of the oil industry; R. Arnold	225	— stress, Role of.....	114, 371
HEALD, K. C., and K. F. MATHER; Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia.....	124, 553	IS THE channel of the Missouri River through North Dakota of Tertiary origin? J. E. Todd.....	120
HIMALAYAS, Geological structure of....	335	— — present the first of a new chapter? A. C. Lane.....	141
HINDS, N. E. A.; Geology of Kauai, Hawaiian Islands.....	125	JADES of middle America; H. S. Washington	220
HISTORICAL sketch of paleopathology; R. L. Moodie.....	197	JASPEROID of the Joplin district, Missouri, Kansas, and Oklahoma; W. S. T. Smith.....	147, 189
HOLDEN, E. T.; Cæruleofibrite, a new mineral	229	JEFFREY, E. C.; Pines of the Mesozoic and their relationship to older and more modern types.....	204
HOT springs of Lassen National Park; A. L. Day and E. T. Allen.....	141	—; Organization of Pennsylvanian anthracite and the peat hypotheses of the origin of coal.....	149
		—; Transitional coals and their bearing on hypotheses of the origin of coals	148
		JOHNSON, D. W.; Retrograding of offshore bars.....	121
		JOHNSON, R. H.; Oil and gas section of the course in economic geology....	224
		—; Role of cross-waves in the formation of tomboloes and points.....	122

	Page		Page
JONAS, A. I., and E. B. KNOPF; Stratigraphy of the crystalline schists of Pennsylvania and Maryland....	110	LIFE eras before the Cambrian; C. R. Keyes	107
JURASSIC formations of western Cuba, Correlation of the.....	159, 639	LICKS and caves of the lower Ohio Valley as repositories of mammalian remains, including those of man; A. M. Miller.....	156
JURUPAITE, a new mineral from Crestmore, California; A. S. Eakle.....	188	LIMESTONES, Significance of red.....	105
KAIPING coal basin of China.....	201	LIMITS of variations in foraminifera; J. A. Cushman.....	208
KANSAN tills in Iowa.....	115	LINDGREN, W.; A recent hot-spring deposit in Bolivia.....	224
KANSAS, Buried granite in.....	96	— suggestion for the terminology of certain ore deposits.....	224
— Coal Measures, Amphibian from....	212	LINDGREN, W., and E. S. BASTIN; Geology of the Braden mine, Chile....	224
—, Jasperoid from.....	189	LONGWELL, C. R., II. D. MISER, R. C. MOORE, and S. PAIGE; Geology of the Colorado River in southeastern Utah.....	122
— of the Joplin district of.....	147	LOOMIS, F. B.; Lower Miocene at Van Tassel, Wyoming.....	211
—, Permian insects of.....	153	—; Upper Pawnee Creek beds.....	211
KANSAS-TEXAS sections, Red Beds and vertebrates of the.....	671	LOUDERBACK, G. D.; Certain marked differential movements in the San Francisco Bay region.....	189
— terrestrial vertebrates.....	208	—; General morphologic features of Basin Range faults.....	96
KATMAI eruption of 1912, Assimilation during	129	LOUGHLIN, G. F.; Ore deposits of Leadville, Colorado.....	149, 225
KAUAI, Geology of.....	125	LOWER Miocene at Van Tassel, Wyoming; F. B. Loomis.....	211
KAY, G. F.; Comparative study of the Nebraskan and Kansan tills of Iowa	115	LULL, R. S.; Restoration of <i>Blastomeryx</i>	211
KEITH, A.; Cambrian succession in northwestern Vermont.....	123	—; Supposed labyrinthodont footprints from the Maryland Carboniferous.	211
KEMP, J. F.; After-effects of igneous intrusion; Presidential address by.	231	—; Variations or specific distinctions: which?	599
—; Isostasy and applied geology..	114, 327	LUNAR petrefactions; F. W. Sardeson..	209
—; Memorial of Henry Platt Cushing.	44	MAGNESITE in 1920, Condition of.....	226
KENNECOTT glaciers of Alaska; A. M. Bateman	527	MAN in Europe, Prehistory of.....	411
KENTUCKY, Ordovician of.....	605	— in the Ohio Valley, Remains of.....	156
—, Trenton of.....	109, 571	MAP of the Pleistocene lakes of the Basin-and-Range province and its significance; O. E. Meinzer... 118,	541
—, Volcanic ash bed in the Ordovician of	152	MAPPING of the United States, Need of expediting	225
KEYES, C. R.; Life eras before the Cambrian	107	MARGINAL belts of the coral seas; W. M. Davis.....	140
—; Memorial of Orestes Hawley Saint John	31	MARSUPIAL from the John Day Oligocene of Logan Butte, Oregon; C. Stock and E. L. Furlong.....	189
KNIGHT, S. H.; Paleozoic-Mesozoic contact throughout Wyoming.....	155	MARTIN, H. T.; Huge amphibian from the Upper Coal Measures of Kansas	212
KNOPF, E. B., and A. I. JONAS; Stratigraphy of the crystalline schists of Pennsylvania and Maryland.....	110	MARYLAND, Crystalline schists of.....	110
KRAUS, E. H.; Mineralogy for students of dentistry.....	229	—, Labyrinthodont footprints from Carboniferous of Maryland.....	211
LABYRINTHODONT footprints from Maryland Carboniferous.....	211	MASSACHUSETTS, Oldhamia in Lower Cambrian of.....	198
LANDSLIDES of the Great Basin ranges.	92	MATHER, K. F.; Front ranges of the Andes between Santa Cruz, Bolivia, and Embarcacion, Argentina.. 138,	703
LANE, A. C.; Is the present the first of a new chapter?.....	141	— and K. C. HEALD; Reconnaissance of the eastern Andes between Cochabamba and Santa Cruz, Bolivia 124,	553
—; Weight of sedimentary rocks per unit volume.....	114, 353	MATTHEW, W. D.; New light on the phylogeny of the Canidae.....	214
LATE Pleistocene history of the lower Mohawk and middle Hudson region; J. H. Stoller.....	117, 515	—; Snake Creek fauna.....	215
— Tertiary mammalian remains from near Alturas, northeastern California; C. Stock.....	188	MECHANICS of the San Andreas fault; B. Willis.....	189
LATENT merosymmetry; E. T. Wherry.	229	MEINZER, O. E.; Map of the Pleistocene lakes of the Basin-and-Range province and its significance..... 118,	541
LASSEN National Park, Hot springs of.	141	MEMORIAL of Henry Platt Cushing; James F. Kemp.....	44
— Peak, New lava from.....	144	— Orestes Hawley Saint John; Charles R. Keyes.....	31
—, Recent eruption of.....	141	— George Frederick Wright; Warren Upham.....	15
LAVA, Surface fusion of.....	142		
LAWSON, A. C.; Isostatic compensation considered as a cause of thrusting.	114, 337		
LEADVILLE, Ore deposits of.....	149, 225		
LEIGHTON, M. M.; Further data on the differentiation of the glacial drift sheets of northern Illinois.....	116		
LEVERETT, F.; Glacial formations on the Coteau des Prairies.....	101		
—; What constitutes the Altamont moraine?	102		

	Page		Page
MEROSYMMETRY, Latent.....	229	NATURE of <i>Taonurus</i> and its use in estimating geologic time; J. J. Gallo-way	199
MERYCHIODONTIDÆ, Primitive characters of.....	212	NEBRASKA, Human type of tooth from.....	214
MESOZOIC-PALEOZOIC contact throughout Wyoming.....	155	NEBRASKAN tills in Iowa.....	115
— pines	204	NECROLOGY	15
METHODS of studying ammonites; Marjorie O'Connell.....	209	NEED of expediting topographic mapping of the United States; F. W. de Wolf.....	225
MILLER, A. M.; Licks and caves of the lower Ohio Valley as repositories of mammalian remains, including those of man.....	156	NEIHART, Montana, Study of supergene processes at.....	226
MILLER, W. J.; Intraformational corrugated rocks.....	98	NELSON, W. A.; Volcanic ash bed in the Ordovician of Tennessee, Kentucky, and Alabama.....	152, 605
—; Sillimanite-schist inclusions in granite	130	NEWARK epoch, Connecticut basin during the.....	87
MINERAL data, Two corrections to.....	230	NEW ENGLAND, Recession of the land-ice in.....	86
— genesis in South Africa.....	229	NEW HAMPSHIRE, Glaciation of.....	86
— veins	330	NEW JERSEY, Franklin zinc ores of....	225
MINERALOGICAL Society; Report of the Committee on Nomenclature and Classification of Minerals.....	228	NEWLAND, D. H.; Source of the sulphates in the Salina beds.....	150
—, Report of the Editor of the.....	228	NEW light on the phylogeny of the Canidæ; W. D. Matthew.....	214
—, Report of Secretary of the.....	228	— source of monochromatic light; A. B. Peck	230
—, Report of Treasurer of the.....	228	NEW YORK sediments, Petrographic studies of.....	107
MINERALOGY: Collophane, a much-neglected mineral.....	189	NOMENCLATURE of Appalachian Coal Measures	111
— for students of dentistry; E. H. Kraus	229	NORTH DAKOTA, Channel of Missouri River through.....	120
—: Jasperoid of the Joplin district....	189	NOVA SCOTIA, Analcite from.....	230
—: Jurupaite from California.....	189	—, Tubular amygdaloid from.....	126
—: Plea for economic.....	229		
MINERALS: Analcite from Nova Scotia.....	230	OCCURRENCE of monosulphide of iron; A. S. Eakle.....	229
—: Cæruleofibrite, a new mineral.....	229	— the Parichnos in certain gymnosperms; E. C. Jeffrey.....	208
—: Crocidolite from Pennsylvania.....	229	O'CONNELL, MARJORIE, and B. BROWN; Correlation of the Jurassic formations of western Cuba.....	159, 639
— from Rhode Island, Crystallography of three.....	229	—: Methods of studying ammonites... 209	
—: Index	230	OFFICERS, Correspondents, and Fellows of the Geological Society.....	173
—: Jades of middle America.....	229	— — — members of the Paleontological Society	217
—: Pyrrhotite	226	—, Election of.....	13
—: Silicates from Crestmore, California.....	230	OFFSHORE bars, Retrograding of.....	121
—: White chlorite from Pennsylvania.....	229	OHIO black shales, Constitution of....	152
MIOCENE at Van Tassel, Wyoming.....	211	— Valley licks and caves as repositories of remains of mammals and of man	156
MISER, H. D., R. C. MOORE, S. PAIGE, and C. R. LONGWELL; Geology of the Colorado River in southeastern Utah.....	122	OIL and gas section of the course in economic geology; R. H. Johnson.....	224
MISSOURI, Jasperoid from.....	189	— fields of the Gulf Coast, Geological work in.....	207
— of the Joplin district.....	147	— geology and isostasy.....	329
— River channel, North Dakota.....	120	— industry, Hazards of the.....	225
MOHAWK and Hudson region, Pleistocene history of.....	515	— invasion into a water-wet sand.....	224
— region, Pleistocene history of.....	117	OKLAHOMA, Devonian of.....	665
MOHAWKIAN and Cincinnati rocks of central Tennessee; R. S. Bassler..	207	—, Jasperoid from.....	189
MONOCHROMATIC light, New source of..	230	— of the Joplin district of.....	147
MONOSULPHIDE of iron.....	229	—, Oriskany of.....	151
MONTANA, Study of supergene processes at Neihart.....	226	OLD and new standards of Pleistocene division in relation to the prehistory of man in Europe; H. F. Osborn and C. A. Reeds.....	140, 411
MONTEZUMA hills; G. A. Wilcox.....	189	OLDHAMIA in the Lower Cambrian of Massachusetts; B. F. Howell.....	198
MOODIE, R. L.; Historical sketch of paleopathology	197	ONTARIO, Silver ores of Cobalt.....	225
MOORE, R. C.; Buried granite in Kansas	96	ORDOVICIAN "hypoparian" genera of trilobites; E. O. Ulrich.....	205
—; Pennsylvanian faunas of north Texas and their correlation.....	199	— of Tennessee, Kentucky, and Alabama, Volcanic ash bed in the....	152
MOORE, R. C., S. PAIGE, C. R. LONGWELL, and H. D. MISER; Geology of the Colorado River in southeastern Utah.....	122	— — Tennessee, Kentucky, and Alabama, Volcanic ash bed in the....	605
MOUNT Monadnock, Vermont—a monteregian hill; J. F. Wolff.....	127	— system	111
MOUNTAIN ranges, Folding of.....	333		
MUSEUM specimens, Care of.....	230		
NATIONAL Research Council, Election of representatives of.....	15		
NATURE of <i>Salterella</i> ; T. H. Clark....	196		

	Page		Page
ORDOVICIC formations of north China; A. W. Grabau.....	202	PLANETESIMAL hypothesis, Astronomical tests of the.....	140
ORE deposits of Leadville, Colorado; G. F. Loughlin.....	149, 225	PLEA for economic mineralogy; O. Bowles	229
OREGON; Marsupial from John Day Oligocene of.....	189	PLEISTOCENE division, Old and new standards of.....	411
OREODON beds of the South Dakota Big Badlands	155	— history of lower Mohawk and middle Hudson region.....	117, 515
ORGANIZATION of Pennsylvanian anthracite and the peat hypotheses of the origin of coal; E. C. Jeffrey.....	149	— lakes of the Basin-and-Range province	118, 541
ORISKANY formation of Oklahoma; C. Schuchert	151, 665	—, Transgressions, regressions, and shoreline displacements during the	140
OSBORN, H. F., and C. A. REEDS; Old and new standards of Pleistocene division in relation to the prehistory of man in Europe.....	140, 411	— subdivisions, Old and new standards of	140
—; Phylogeny and nomenclature of the Proboscidea	215	— vertebrate faunas, Discussion of....	156
PAIGE, S., C. R. LONGWELL, H. D. MISER, and R. C. MOORE; Geology of the Colorado River, southeastern Utah.....	122	POLICY Committee of the Council, Report of.....	136
PALACHE, C.; Some problems of mineral genesis in South Africa; Presidential address by.....	229	POSSIBLE habits of Cephalopods and trilobites; P. E. Raymond.....	197
PALEOPATHOLOGY, Sketch of.....	197	— tillite at Levis, Quebec; R. W. Sayles ..	99
PALEONTOLOGICAL Society, Election of officers and members of the.....	195	POWERS, S.; Reflected hills in petroleum geology.....	226
—, Proceedings of.....	191	PRECIOUS stones, Geological and geographical occurrence of.....	226
—, Report of Council of.....	193	PRELIMINARY notes on some regularly banded argillites which suggest seasonal deposition; R. W. Sayles ..	133
PALEOZOIC corals, Unattached simple..	201	— — the shoreline of glacial lake Nashua, near Fitchburg, Massachusetts; T. C. Brown.....	118
PALEOZOIC-MESOZOIC contact throughout Wyoming; S. H. Knight.....	155	PREHISTORY of man in Europe.....	411
— systems, Revision of the.....	112	PRE-PENNSYLVANIAN rocks of Virginia..	98
PARICHNOS of Bertrand.....	208	PRESANTATION of loving cup to B. K. Emerson	134
PARSONS, A. L.; Analcite from Nova Scotia, with a discussion of analcite analyses in general.....	230	PRESIDENTIAL address by J. F. Kemp... ..	113, 231
—; Care of museum specimens.....	230	— — — R. A. F. Penrose, Jr.....	224
— and T. L. WALKER; Tubular amygdaloid from Nova Scotia.....	126	— — — C. Palache.....	229
PAWTUCKAWAY Mountains, Geology of.	128	— — — T. W. Stanton.....	255
PAWNEE Creek beds.....	211	PRIMARY native silver ores near Wickenburg, Arizona, and their bearing on the genesis of the silver ores of Cobalt, Ontario; E. S. Bastin.....	225
PAYETTE formation.....	203	PRIMITIVE and carnivore-like characters of the Merychiodontidae; M. R. Thorpe	212
PEAT hypotheses of origin of coal....	149	PROBABLE occurrence of massive troilite in serpentine; A. S. Eakle.....	188
PECK, A. B.; New source of monochromatic light.....	230	— origin of certain vein structures; L. C. Graton.....	224
PENEPLAINS and the geographical cycle; W. M. Davis.....	121, 581	PROBOSCIDEA, Phylogeny and nomenclature of the.....	215
PENNSYLVANIA anthracite, Origin of... ..	149	PROCEEDINGS of the First Annual Meeting of the Society of Economic Geologists, held at Amherst, Massachusetts, December 28-30, 1921; S. H. Ball, Secretary.....	223
—, Crystalline schists of.....	110	— — — Second Annual Meeting of the Mineralogical Society of America, held at Amherst, Massachusetts, December 29, 1921; H. P. Whitlock, Secretary.....	227
—, White chlorite from.....	229	— — — Thirteenth Annual Meeting of the Paleontological Society, held at Amherst, Massachusetts, December 28-30, 1921; R. S. Bassler, Secretary	191
PENNSYLVANIAN faunas of north Texas and their correlation; R. C. Moore..	199	— — — Thirty-fourth Annual Meeting of the Geological Society of America, held at Amherst, Massachusetts, Wednesday-Friday, December 28-30, 1921; E. O. Hovey, Secretary	1
PENROSE, R. A. F., JR.; The Society of Economic Geologists—its sphere and future; Presidential address by ..	224	— — — Twentieth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 26, 1921; A. F. Rogers, Secretary....	187
PERMIAN insects of Kansas, Environment of.....	153		
— of west Texas, Cavern deposits in the	153		
PETROGRAPHIC notes on the Franklin, New Jersey, zinc ores; W. C. Bowen ..	225		
— studies of some New York sediments; H. L. Alling.....	107		
PETROLEUM geology, Reflected hills in..	226		
—, Improved methods of extracting....	224		
— mining, Use of foraminifera in determining underground structure in..	145		
PETROLOGY: Graphic study of igneous rock series.....	617		
PHYLLITE, Age of the Talladega.....	151		
PHYLOGENY and nomenclature of the Proboscidea; H. F. Osborn.....	215		
PINES of the Mesozoic and their relationship to older and more modern types; E. C. Jeffrey.....	204		

	Page		Page
PROPOSED new nomenclature of the Appalachian Coal Measures; G. H. Ashley	111	RESTORATION of <i>Blastomeryx</i> ; R. S. Lull	211
PROUTY, W. F.; Age of the Talladega phyllite	151	— <i>Eporeodon socialis</i> , Marsh; M. R. Thorpe	213
PUBLICATION rules of the Geological Society	169	RESULTS obtained by improved methods of extracting petroleum; R. B. Bossler	224
PURCELL Range, Relation of Canadian Rockies to	91	RETROGRADING of offshore bars; D. W. Johnson	121
PUTNAM, G. R.; Condition of the earth's crust and the earlier American gravity observations	113, 287	RHODE ISLAND minerals, Crystallography of three	229
PYRRHOTITE, Some etching tests on	226	ROCK density and isostasy	114
QUANTITATIVE study of the derivation of North American Algonkian sediments; A. C. Trowbridge and W. S. Glock	108	ROGERS, A. F.; A study of crystal symmetry	229
QUEBEC, Alnoitic from Isle Cadieux	130	—; Collophane, a much-neglected mineral	189
—, Tillite at Levis	99	—; Tridymite-orthoclase rock, a new metamorphic rock type from Imperial County, California	129
RANCHO LA BREA, Flora of the	204	—, Secretary; Proceedings of the Twentieth Annual Meeting of the Cordilleran Section of the Geological Society of America, held at Berkeley, California, March 26, 1921	187
RAYMOND, P. E.; Possible habits of cephalopods and trilobites	197	—; Use of plans and elevations in teaching geometrical crystallography	229
—; Trenton of central Tennessee and Kentucky	109, 571	RÔLE of cross-waves in the formation of tombolos and points; R. H. Johnson	122
RECENT eruption of Lassen Peak; A. L. Day and E. T. Allen	141	— isostatic stress; B. Willis	114, 371
— geological work in Gulf Coast oil fields; E. T. Dumble	207	RUNNER, J. J.; Gold-bearing cumingtonite schists of the Black Hills, South Dakota	225
RECONNAISSANCE of the eastern Andes between Cochabamba and Santa Cruz, Bolivia; K. C. Heald and K. F. Mather	124, 553	—; Index minerals for the interpretation of geological history	230
RED Beds and terrestrial vertebrates of the Appalachian	671	SAINT JOHN, O. H., Bibliography of	43
— limestones and their geologic significance; J. J. Galloway	105	—, Memorial of	31
REEDS, C. A., and H. F. OSBORN; Old and new standards of Pleistocene division in relation to the prehistory of man in Europe	140, 411	SALINA beds, Source of sulphates in the	150
—; Transgressions, regressions, and shoreline displacements during the Pleistocene	140	SALTERELLA, Nature of	196
REFLECTED hills in petroleum geology; S. Powers	226	SAN ANDREAS fault, Mechanics of the	189
REGISTER of the Amherst Meeting	160	SAND grains, Interpretation of	104
— of the Paleontological Society	216	SAN SALVADOR, Basaltic lava from	143
— California Meeting of Cordilleran Section	189	SAYLES, R. W.; Preliminary notes on some regularly banded argillites which suggest seasonal deposition	133
REID, H. F.; Isostasy and earth movements	114, 317	—; Possible tillite at Levis, Quebec	99
—; Some astronomical tests of the planetesimal hypotheses	140	SCHUCHERT, C.; Devonian of Oklahoma, with special reference to the Oriskany and Camden formations	665
RELATION of deep-seated faults to surface structure in the region northeast of the Yellowstone Park plateau; W. T. Thom, Jr.	99	—; Oriskany of Oklahoma	151
RELATIONSHIP of the Great Basin and Great Plains fauna; E. L. Troxell	210	—; The Andean geosyncline	90
REPORT of the Auditing Committee	113	SEASONAL deposition suggested by banded argillites	133
— of the Paleontological Society	207	SECRETARY'S report	6
— Council	6	SEDIMENTS, Weight per unit volume of	114
— Committee on Policy	136	SHALES, Constitution of Ohio black	152
— of the Paleontological Society	193	SHANNON, E. V., and E. T. WHERRY; Crocidolite from eastern Pennsylvania	229
— Committee on Teaching of Geology; H. F. Cleland	55	—; White chlorite from eastern Pennsylvania	229
— Editor	11	SHEPARD, F. P.; Structural relation of the Purcell Range to the Canadian Rockies	91
— Secretary	6	SHIU, China, Antimony mines of	149
— Treasurer	9	SILICATES of the contact limestones of Crestmore, California; A. S. Eakle	230
RECESSION of the land-ice in New England; E. Antevs	86	SILLIMANITE-SCHIST inclusions in granite; W. J. Miller	130
REVISION of the Paleozoic systems. Part II: The Ordovician system; E. O. Ulrich	112	SILVER ores from Arizona and Ontario	225
		SINCLAIR, W. J.; Stratigraphy of the lower Oreodon beds of the South Dakota Big Badlands	155
		—; Hyracodons from the Big Badlands of South Dakota	209
		SKIRVIN, O. W.; Experimental study of the invasion of oil into a water-wet sand	224

	Page		Page
SMITH, E. S. C.; Geology of the Paw-tuckaway Mountains.....	128	SURFACE fusion of lava; J. S. Diller...	142
SMITH, W. S. T.; Jasperoid of the Joplin district, Missouri, Kansas, and Oklahoma	147, 189	SYMPOSIUM on isostasy.....	113
SNAKE River fauna; W. D. Matthew...	215	TALLADEGA phyllite, Age of the.....	151
SOME astronomical tests of the planetesimal hypotheses; H. F. Reid....	140	TAONURUS, Nature of.....	199
—cavern deposits in the Permian in west Texas; J. A. Udden.....	153	TEACHING of Geology, Report of Committee on.....	55
—considerations touching on isostasy; H. O. Wood.....	303	TENNESSEE, Ordovician of.....	605
—etching tests on pyrrhotite; H. C. Boydell	226	—, Trenton of central.....	109, 571
—new aspects of the geology at Cobalt; A. R. Whitman.....	189	—, Volcanic ash bed in the Ordovician of	152
—facts bearing on correlations of Chester formations; E. O. Ulrich..	805	TERTIARY mammalian remains from Alturas, California.....	188
—problems connected with the Dakota sandstone; Presidential address by T. W. Stanton.....	203, 255	—of California, Marine.....	188
—of mineral genesis in South Africa; Presidential address by C. Palache	229	TEXAS-KANSAS sections, Red Beds and terrestrial vertebrates of the....	671
SOURCE of the sulphates in the Salina beds; D. H. Newland.....	150	—terrestrial vertebrates.....	208
SOUTH DAKOTA, Cummingtonite schists of	225	—, Pennsylvanian faunas of.....	199
—, Oreadon beds of the Big Badlands of	155	THE Andean geosyncline; C. Schuchert,	90
—, Hyracodons from.....	209	—Society of Economic Geologists—its sphere and future; Presidential address by R. A. F. Penrose, Jr...	224
STAGES of the Ice Age; W. Upham.	100, 491	THEORY of isostasy—a geological problem; W. Bowie.....	113, 273
STANTON, T. W.; Some problems connected with the Dakota sandstone; Presidential address by.....	203, 255	THOM, W. T., JR.; Relation of deep-seated faults to surface structure in the region northeast of the Yellowstone Park plateau.....	99
STOCK, C.; Late Tertiary mammalian remains from near Alturas, northeastern California.....	188	THORPE, M. R.; <i>Aræocyon</i> , a probable old world migrant.....	214
—and E. L. FURLONG; Marsupial from the John Day Oligocene of Logan Butte, Oregon.....	189	—; Primitive and carnivore-like characters of the Merycoidodontidae...	212
STOLLER, J. H.; Late Pleistocene history of the lower Mohawk and middle Hudson region.....	117, 515	—; Restoration of <i>Eporeodon socialis</i> , Marsh	213
STONE, R. W.; Condition of magnesite in 1920.....	226	THRUSTING, Isostatic compensation as cause of.....	337
STOSE, G. W.; Structure of the pre-Pennsylvanian rocks of the Big Stone Gap area, Wise County, Virginia	98	TILLITE at Levis, Quebec.....	99
STRATA near Stuart, Iowa; J. L. Tilton	153, 689	TILTON, J. L.; Strata near Stuart, Iowa	153, 689
STRATIGRAPHY of the crystalline schists of Pennsylvania and Maryland; E. B. Knopf and A. I. Jonas.....	110	TODD, J. E.; Is the channel of the Missouri River through North Dakota of Tertiary origin?.....	120
—lower Oreadon beds of the South Dakota Big Badlands; W. J. Sinclair	155	TOMBOLOES and points, Formation of..	122
STRESSING economics in the teaching of economic geology; E. S. Bastin...	224	TOOTH of almost human type from the Lower Pliocene Snake Creek beds of western Nebraska; H. J. Cook..	214
STRUCTURE of the Connecticut basin during the Newark epoch; W. G. Foye	87	TRANSGRESSIONS, regressions, and shoreline displacements during the Pleistocene; C. A. Reeds.....	140
—pre-Pennsylvanian rocks of the Big Stone Gap area, Wise County, Virginia; G. W. Stose.....	98	TRANSITIONAL coals and their bearing hypotheses of the origin of coals; E. C. Jeffrey.....	148
STRUCTURAL relation of the Purcell Range to the Canadian Rockies; F. P. Shepard.....	91	TRASK, P. D.; Discussion of the age of the Briones formation of middle California	189
STUART, Iowa, Strata near.....	153, 689	TREASURER'S report.....	9
STUDY of supergene processes at Nehart, Montana; M. E. Hurst.....	226	TRENTON of central Tennessee and Kentucky; P. E. Raymond.....	109, 571
SULPHATES in the Salina beds, Source of the.....	150	TRIDYMIITE-ORTHOCLASE rock, a new metamorphic rock type from Imperial County, California; A. F. Rogers	129
SUPPLEMENT to the bibliography and catalogue of the fossil vertebrates of North America; O. P. Hay....	203	TRILOBITES and cephalopods, Possible habits of.....	197
SUPPOSED labyrinthodont footprints from the Maryland Carboniferous; R. L. Lull.....	211	—, "Hypoparian" genera of.....	205
		TROWBRIDGE, A. C., and W. S. Glock; Quantitative study of the derivation of North American Algonkian sediments	108
		Troxell, E. L.; Relationship of the Great Basin and Great Plains fauna	210
		—; Fossils of the Connecticut Valley..	209
		TUBULAR amygdaloid from Nova Scotia; T. L. Walker and A. L. Parsons...	126
		Two corrections of mineral data; N. L. Bowen	230

	Page		Page
UDDEN, J. A.; Some cavern deposits in the Permian in west Texas.....	153	WALKER, T. L., and A. L. PARSONS; Tubular amygdaloid from Nova Scotia	126
ULRICH, E. O.; Few more facts bearing on the correlation of the Chester formation	208	WASHINGTON, H. S.; Deccan traps and other plateau basalts.....	146, 765
—; Ordovician "hypoparian" genera of trilobites	205	—; Isostasy and rock density.....	114, 375
—; Revision of the Paleozoic systems. Part II: The Ordovician.....	112	—; Jades of middle America.....	229
—; Some new facts bearing on correlations of Chester formations.....	805	WEIGHT of sedimentary rocks per unit volume; A. C. Lane.....	114, 353
UNATTACHED simple Paleozoic corals; A. F. Foerste.....	201	WHAT constitutes the Altamont moraine? F. Leverett.....	102
UNDERDRAG of the Great Basin ranges..	92	WHERRY, E. T.; Latent merosymmetry. — and E. V. SHANNON; Crocidolite from eastern Pennsylvania.....	229
UPHAM, WARREN; Memorial of George Frederick Wright.....	15	— —; White chlorite from eastern Pennsylvania	229
—; Stages of the Ice Age.....	100, 491	WHITE chlorite from eastern Pennsylvania; E. T. Wherry and E. V. Shannon	229
UPPER Pawnee Creek beds; F. B. Loomis	211	WHITLOCK, H. P., Secretary; Proceedings of the Second Annual Meeting of the Mineralogical Society of America, held at Amherst, Massachusetts, December 29, 1921.....	227
USE of foraminifera in determining underground structure, especially in petroleum mining; J. A. Cushman.	145	WHITMAN, A. R.; Some new aspects of the geology at Cobalt.....	189
— plans and elevations in teaching geometrical crystallography; A. F. Rogers	229	WILCOX, G. A.; Montezuma hills.....	189
UTAH, Geology of Colorado River in southeastern	122	WILLIS, B.; Mechanics of the San Andreas fault.....	189
VALUE of the physical characters of sand grains in the interpretation of the origin of sandstones; J. J. Galloway	104	—; Rôle of isostatic stress.....	114, 371
VARIATIONS or specific distinctions: which? R. S. Lull.....	599	WISCONSIN ice-sheet, Ablation of the eastern lobe of.....	117
VEIN structures, Origin of.....	224	WOLFF, J. E.; Mount Monadnock, Vermont—a monteregian hill.....	127
VERMONT, Cambrian succession in.....	123	WOOD, H. O.; Some considerations touching on isostasy.....	114, 303
—, Mount Monadnock a monteregian hill in.....	127	WRIGHT, G. F., Bibliography of.....	22
VERTEBRATE faunas of the Pleistocene.	156	—, Memorial of.....	15
VIRGINIA, Pre-Pennsylvanian rocks of..	98	WYOMING Lower Miocene at Van Tassel	211
VOLCANIC activity, A source of heat in.	144	—, Paleozoic-Mesozoic contact throughout	155
— ash beds in the Ordovician of Tennessee, Kentucky, and Alabama; W. A. Nelson.....	152, 605	YELLOWSTONE Park plateau, Deep-seated faults of region northeast of.....	99
VOTE of thanks.....	136		

THE GEOLOGICAL SOCIETY OF AMERICA

OFFICERS, 1922

President:

CHARLES SCHUCHERT, New Haven, Conn.

Vice-Presidents:

HENRY S. WASHINGTON, Washington, D. C.

ROBERT T. HILL, Glendale, Calif.

W. D. MATTHEW, New York City

T. L. WALKER, Toronto, Canada

Secretary:

EDMUND OTIS HOVEY, American Museum of Natural History,
New York, N. Y.

Treasurer:

EDWARD B. MATHEWS, Johns Hopkins University, Baltimore, Md.

Editor:

J. STANLEY-BROWN, 26 Exchange Place, New York, N. Y.

Councilors:

(Term expires 1922)

T. W. VAUGHAN, Washington, D. C.

GEORGE F. KAY, Iowa City, Iowa

(Term expires 1923)

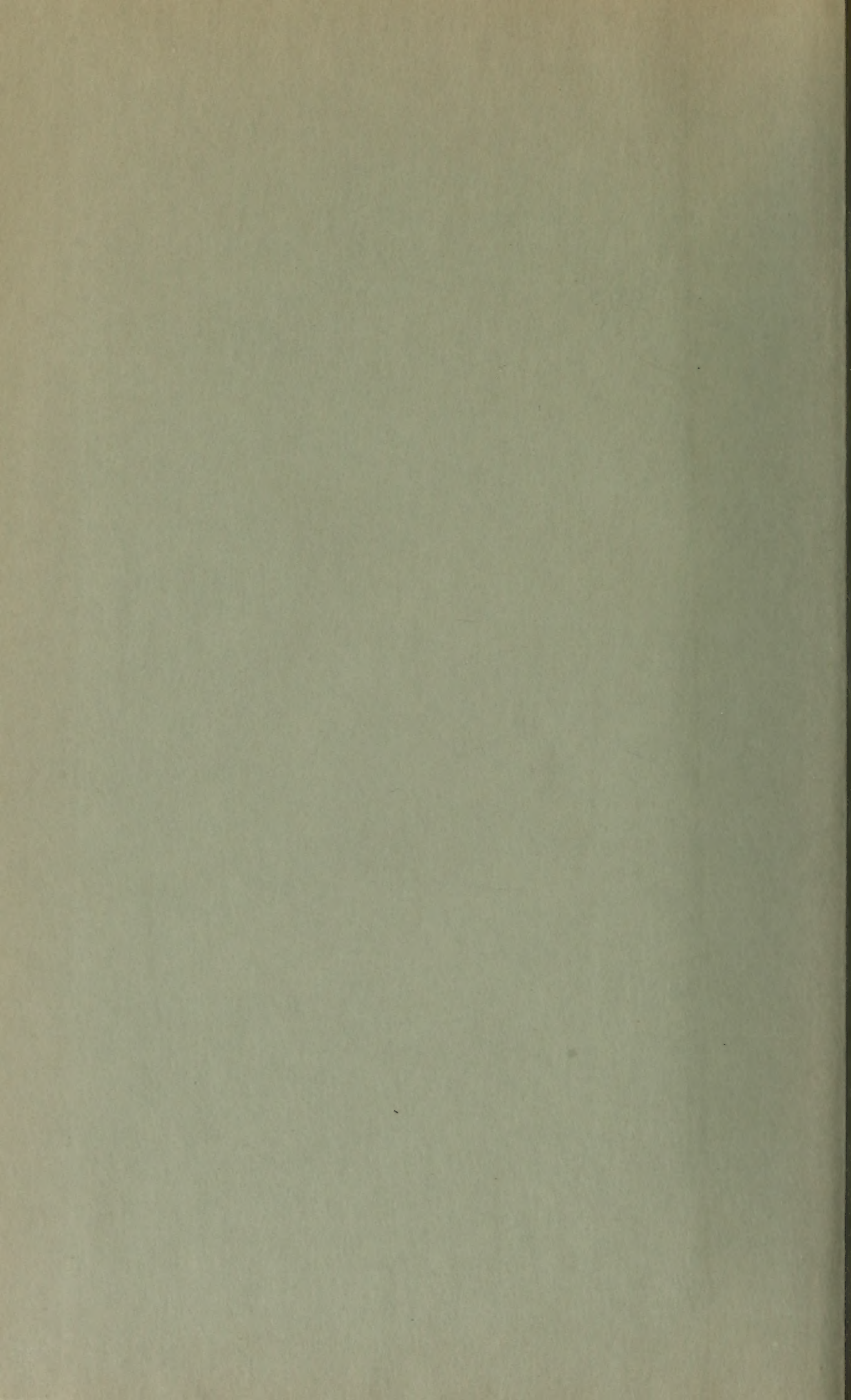
L. C. GRATON, Cambridge, Mass.

G. D. LOUDERBACK, Berkeley, Calif.

(Term expires 1924)

E. S. BASTIN, Chicago, Ill.

L. G. WESTGATE, Delaware, Ohio



SMITHSONIAN INSTITUTION LIBRARIES



3 9088 01309 2044